IDENTIFICATION AND ANALYSIS OF OPERATIONAL AND BEHAVIOURAL RISKS EMERGING AND PROPAGATING IN SUPPLY CHAINS: A MULTI-METHOD APPROACH

by

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DECLARATION OF ORIGINALITY OF RESEARCH

The thesis is submitted in fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) in the Macquarie Graduate School of Management (MGSM), Macquarie University. Except as acknowledged in the references, the material included in the thesis represents the original work and contributions of the author.

I hereby certify that the research described in this dissertation has not been submitted for a higher degree to any other university or institution.

[Ethics approval- Ref: 5201500565, Appendix 9]

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ABBREVIATIONS USED IN THESIS

ABDC	Australian Business Deans Council
ANZAM	Australia and New Zealand Academy of Management
APICS	American Production and Inventory Control Society
AVE	Average Variance Extracted
CCDEA	Chance-Constrained DEA
CCR	Charnes, Cooper, & Rhodes
CIT	Critical Incident Technique
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
IECD	Interest Expense on Customer Deposits
IIL	Interest Income on Loans
IT	Information Technology
NF	Number of Referrals
NFC	Net Fees and Commissions
NPL	Non-Performing Loans
NVSP	Net Value of Services Provided
OIE	Other Interest Expenses
OII	other interest income
OOE	Other Operating Expenses
OOI	Other Operating Incomes
OOSE	Other Outsourcing Expenses
OSE	Outsourcing Expenses
PE	Personnel Expenses
PFR	Proportion of Fruitless Referrals
PT	Prospect Theory
QoR	Quality of Relations
RaST	Risk-aware Service Triad
RI	Risk Index
SBM	Slacks-Based Measure
SCOR	Supply Chain Operations Reference (model)
SCRM	Supply Chain Risk Management
SCV	Supply Chain Vulnerability
TFN	Triangular Fuzzy Numbers

PUBLICATIONS BASED ON THE CURRENT RESEARCH

Peer-Reviewed Journal Articles and Book Chapters

Pournader, M., Kach, A. P., Fahimnia, B., & Sarkis, J. (2016). Outsourcing Performance Quality Assessment Using Data Envelopment Analytics. *International Journal of Production Economics (Rank A*)*, Jul. 2016. (In press).

Pournader, M., Rotaru, K., Kach, A., & Razavi Hajiagha, S. H. (2016). An Analytical Model for System-wide and Tier-specific Assessment of Resilience to Supply Chain Risks. *Supply Chain Management: An International Journal (Rank A)*, *21*(5). (Published).

Pournader, M., Kach, A. P., Razavi Hajiagha, S. H., & Emrouznejad, A. Investigating the Impact of Behavioral Factors on Supply Network Efficiency: Insights from Banking's Corporate Bond Networks. *Annals of Operations Research (Rank A)*. (Under review).

Pournader, M., & Rotaru, K. The Application of Graph Theory for Vulnerability Assessment in Service Triads. *Journal of Operational Research Society (Rank A)*. (Under review).

Rotaru, K., & **Pournader, M.** Modeling Risk Emergence and Propagation in Buyer-Supplier-Customer Relationships: Towards a Typology of Risk-aware Service Triads. In Y. Khojasteh (Ed.), *Supply Chain Risk Management: Advanced Tools, Models, and Developments*. Springer (Forthcoming Oct. 2016).

Peer-Reviewed Conference Papers

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Pournader, M., Kach, A., Najmae,i A., & Keblis, M. (2014). *Identifying Drivers of Supply Chain Vulnerability: An Integrative Framework*. ANZAM Conference, Sydney, NSW, Dec. 2014 (Oral presentation-Competitive Session).

Working Papers

Pournader, M., Narayanan, A., & Keblis M. Risk Attitudes and Ordering Behavior in Multi-echelon Supply Chains, Apr. 2016 (Working paper).

ABSTRACT

The study of supply chain risks can be conducted from various perspectives, including types of risks and supply chain structure. First, from the aspect of the types of supply chain risks, the thesis investigates operational and behavioural risks both separately and in tandem. For operational risks, the proposed research model tackles a critical research problem in supply chain risk literature, which revolves around making a link between supply chain resilience and risk assessment. Outsourcing malfunctions and risks associated with them are analysed as a specific type of operational risk that is prevalent in modern supply chains. For behavioural risks, the risk attitudes of decision makers and their impact on inventory decisions are investigated. Another study, conducted at the intersection of behavioural and operational risks, shows the importance of considering both types of the aforementioned risks while assessing vulnerabilities in supply chains. Second, the research adopts the viewpoint of supply chain structure, investigating supply chains and their vulnerability to risks in forms of service supply networks, in particular in service triads.

Most of the studies adopt a multi-method approach, proposing analytical models to assess supply chain vulnerability to risks and testing these models using surveys, interviews, archival data or behavioural experiments.

-CHAPTER ONE-

-INTRODUCTION-

1.1. Motivation

Since the beginning of the 21st century, managing risks in supply chains has become a topic of a great significance, widely debated in both research and practice alike (Sodhi, Son, & Tang, 2012; Zsidisin & Wagner, 2010). There are many reasons behind the growing interest surrounding supply chain risk identification and analysis, including the globalization and ever-increasing outsourcing of manufacturing processes to countries with lower production costs and complex technological advancements (Christopher & Peck, 2004; Thun & Hoenig, 2011; Wagner & Neshat, 2010), all contributing towards the increasing vulnerability of modern supply chains. Moreover, it has been argued over the past few years that the severity and frequency of supply chain disruptions has been steadily on the rise (Craighead, Blackhurst, Rungtusanatham, & Handfield, 2007; Ritchie & Brindley, 2007). According to the annual "Supply Chain Resilience 2013" report conducted by the UK Business Continuity Institute (Glendon & Bird, 2013b), 75% of the respondents were affected by at least one source of supply chain risk and 15% experienced loss of more than £1 million in 2012–2013. There are also numerous cases of risks, realized as disruptions, in supply chains that culminated in significant losses over the past years (e.g., Blackhurst, Scheibe, & Johnson, 2008; Jüttner, 2005; Rao & Goldsby, 2009a). Thus, identifying the full spectrum of supply chain risks, assessing them and managing adverse consequences caused by supply chain disruptions are vital for assuring transparency among supply chain partners.

There are, however, several issues in the study of supply chain risks that are yet to be investigated and addressed to achieve more efficient and robust practices of supply chain risk management.

The first issue pertains to supply chain resilience and how it could be enhanced in both tier-specific and system-wide supply chain processes by understanding and prioritizing risks threatening those processes. Several gaps exist in this line of research. The first gap is that the literature (Ambulkar, Blackhurst, & Grawe, 2015; Jüttner & Maklan, 2011) has hitherto reported mainly on system-wide supply chain resilience and has not considered resilience of the individual supply chain members. Second, there has not been a clear link between supply chain resilience and risks making it complicated to discern which elements for resilience assessment would help the most in managing the consequences of supply chain disruptions.

The second issue revolves around the nature of risks studied so far in the supply chain risk literature. The study of risks in supply chains has long been confined to operational risks, ruling out the behavioural issues associated with decision-making processes that could bolster the effect of operational risks or add to supply chain vulnerability independently (Ellis, Henry, & Shockley, 2010). Despite the prominence of this topic, only a few research papers have investigated the intersections of operational and behavioural risks in supply chains (Ghadge, Dani, & Kalawsky, 2012). Moreover, in the behavioural domain of operations and supply chain management research, decision makers' preferences toward risk and its effect on supply chain decisions offers promising avenues for research. The research presented in this thesis investigated inventory decisions and risk preferences in supply chains.

The third issue surrounding the supply chain risk literature is the structure of supply chains and how this could affect risk and vulnerability assessments in supply chains. Studying risks in modern supply chains in forms of dyadic structures of buyer-buyer, buyer-supplier or buyer-customer does not fully correspond to the complexities of modern supply chains (Carter, Rogers, & Choi, 2015; Mena, Humphries, & Choi, 2013). One of the studies in this thesis revolves around service triads and assessment of their vulnerability in corporate banks. The scarcity of proper analytical tools to assess vulnerability in service triads was another motivation behind this study.

1.2. Research questions and objectives

The first part of the thesis (Chapter 2) investigates operational risks in supply chains, with several research questions addressing risk and resilience assessment:

- Is there a need to conduct assessment of risk and resilience from both system-wide and tier-specific aspects?

- Do individual contributions of supply chain partners affect the overall supply chain resilience assessments?

- How can clear links be established between risk factors and resilience practices in supply chains?

Aligned with the same stream of research, another study of operational risks presented here (Chapter 2/Section 2.4) focused specifically on supply chain outsourcing and how the same analytical model providing risk and resilience assessment could be customized and adopted to outsourcing performance assessment in supply chains. The main objective of this paper was to identify supply chains tiers that threaten the overall flow of outsourced supply chain processes by their inefficient performance.

Moving toward the interplay between operational and behavioural risks in supply chains, in the second part of the thesis (Chapter 3), we aim to answer the following question:

- Are supply chain risk assessment efforts more accurate and compatible with real-world practices if we incorporate the behavioural risks of decision making? If so, how could this be achieved? And how could the differences produced by the new model be measured, compared with already existing models for operational risk assessment?

The next research question, addressed in Chapter 3/Section 3.3, is associated with the actual risk preferences of supply chain decision makers and how it affects their ordering behaviour. More specifically:

- Can risk-aversion, risk-seeking, or loss-aversion models explain ordering behaviour of decision makers in supply chains?

Finally, the third part of the thesis (Chapter 4) looks at the study of risks emerging and propagating in supply chains through the prism of triads and in particular service triads. Here the research objective is to:

- Use the toolset of graph theory, to model different cross-organizational pathways according to which risks can emerge and propagate in service triads seen as an elementary form of service supply networks,
- Provide a method for vulnerability assessment of the suggested graph models of service triads, taking into consideration the typology and direction of the cross-organizational relationships within graph models of supply chain triads, and
- Illustrate the applicability of the suggested approach to modelling and vulnerability assessment in supply chain service triads in the service industry context.

1.3. Theoretical background

The papers included in Chapter 2 (study of operational risks) and Chapter 4 (study of vulnerability in service triads) draw upon the emerging theory of supply chain (Carter et al., 2015).

Briefly, the emerging theory of supply chain by Carter et al. (2015) conceptualizes supply chains as networks comprising interconnected companies or 'complex adaptive systems'. This means that each supply chain member can be construed as a self-organizing adaptive agent with interdependent behaviour that affects the whole supply chain system (Nair, Narasimhan, & Choi, 2009). This view of supply chains in the context of risk assessment calls for a holistic risk management approach that investigates supply chains from both tier-specific and system-wide perspectives.

1.4. Methodological background

A multi-methodological approach was adopted for most publications presented in this thesis. Such approaches apply multiple methodologies from the same or different disciplines and are ideal for studying a phenomenon and understanding its complexities (Boyer & Swink, 2008; Sanders & Wagner, 2011). Indeed, the increased rigor and reliability of adopting multi-method approaches results in "greater insights into research problems, reduction in the myopic, disciplined-based perspective, and greater potential for innovative SCM [Supply Chain Management] breakthroughs" (Sanders and Wagner, 2011, p. 318). Choi, Cheng, and Zhao (2016, p. 380) define multi-methodological approach in production and operations management studies as "… an approach for OM [Operations Management] research in which at least two distinct OM research methods are employed nontrivially to meet the research goals". They subsequently elaborate on their discussions on multi-method approaches by identifying the two-by-two combinations of analytical modelling, quantitative empirical and case-study research methods (based on the classifications of Sodhi and Tang (2014)) and their application to production and operations management studies. In addition to this classification, exploratory and qualitative research methods can also generally be included in multi-method approaches (Singhal & Singhal, 2012a, 2012b).

1.5. Chapter summary and thesis outline

This chapter has discussed the motivations behind the three main parts of the research, outlined the research questions and objectives, and briefly explained the theoretical and methodological foundations of the papers presented in the thesis. The papers in each chapter are listed in Table 1.1.

Chapter 2 reviews the literature on operational supply chain risks (Section 2.2), identifying and discussing two different categorizations of risks. Sections 2.3 and 2.4 present two papers discussing risk and resilience, and outsourcing performance assessments in supply chains, respectively.

Chapter 3 provides an overview of the literature in behavioural supply chain and operations management (Section 3.1), followed by two papers. The first paper (Section 3.2) investigates behavioural and operational risks in a banking service supply chain. The second paper (Section 3.3) studies ordering behaviour of decision makers in supply chains considering risk-aversion, risk-seeking and loss-aversion behaviours.

Chapter 4 contains a book chapter (Section 4.2) and a paper (Section 4.3) discussing vulnerability assessment in service triads based on the principles of graph theory.

Chapter 5 presents a summary of the results, conclusions, implications for future research and research limitations.

Table 1.1 Order of the papers contained in each chapter

Chapter 2	**1- Pournader, M.**, Kach, A., Najmae,i A., & Keblis, M. (2014). *Identifying Drivers of Supply Chain Vulnerability: An Integrative Framework*. ANZAM Conference, Sydney, NSW, Dec. 2014 (Oral presentation-Competitive Session). [Section 2.2] **2- Pournader, M.**, Rotaru, K., Kach, A., & Razavi Hajiagha, S. H. (2016). An Analytical Model for System-wide and Tier-specific Assessment of Resilience to Supply Chain Risks. *Supply Chain Management: An International Journal (Rank A)*, *21*(5). (Published) [Section 2.3] **3- Pournader, M.**, Kach, A. P., Fahimnia, B., & Sarkis, J. (2016). Outsourcing Performance Quality Assessment Using Data Envelopment Analytics. *International Journal of Production Economics (Rank A*)*, Jul. 2016. (In press). [Section 2.4]
Chapter 3	**4- Pournader, M.**, Kach, A. P., Razavi Hajiagha, S. H., & Emrouznejad, A. (Sep. 2016). Investigating the Impact of Behavioral Factors on Supply Network Efficiency: Insights from Banking's Corporate Bond Networks. *Annals of Operations Research (Rank A)*. (Under review). [Section 3.2] **5- Pournader, M.**, Narayanan, C., & Keblis M. (2016). *Prospect Theory and Ordering Behavior in Multi-echelon Supply Chains*. MSOM Conference, Auckland, New Zealand, Jun. 2016 (Oral presentation) [Section 3.3] **6- Pournader, M.**, Narayanan, A., & Keblis M. Risk Attitudes and Ordering Behavior in Multi-echelon Supply Chains, Apr. 2016 (Working paper). [Section 3.3]
Chapter 4	**7-** Rotaru, K., & **Pournader, M.** Modeling Risk Emergence and Propagation in Buyer-Supplier-Customer Relationships: Towards a Typology of Risk-aware Service Triads. In Y. Khojasteh (Ed.), *Supply Chain Risk Management: Advanced Tools, Models, and Developments*. Springer (Forthcoming Oct. 2016). [Section 4.2] **8- Pournader, M.**, & Rotaru, K. The Application of Graph Theory for Vulnerability Assessment in Service Triads. *Journal of Operational Research Society (Rank A)*. (Under review). [Section 4.3]

-CHAPTER TWO-

-OPERATIONAL RISKS AND RESILIENCE IN SUPPLY CHAINS-

2.1. Introduction

The literature contains no unique definition of supply chain [operational] risks,[1] but rather a spectrum of definitions provided by scholars to tackle certain aspects of risk analysis and management in supply chains. For instance, while March and Shapira (1987) provided the first definition of supply chain risks as variations and uncertainties in the supply chain outcomes, Zsidisin (2003a) defined supply risks as occurrences where companies and supply chains cannot manage the consequences of these particular incidents. Others, such as Jüttner, Peck, and Christopher (2003, p. 200), built on the definition by March and Shapira (1987) and defined supply chain risks as "a mismatch between supply and demand" that could cause disruptions in the flow of material, information and products throughout the supply chain. Similar definitions of supply chain risks have been provided by others (e.g., Peck, 2006; Tang & Musa, 2011), which more or less emphasize the likelihood of occurrence and negative consequences of risks and also sources and operations that instigate those risks (Ritchie & Brindley, 2007). Traditionally, these types of risks are considered to stem from operations related to three main flows in supply chains: material flow, information flow and financial flow (Tang, 2006; Tang & Musa, 2011), and hence they are considered operational risks. The definition of operational supply chain risks in this thesis follow the previous literature on supply chain risks, with the exception that the current research considers operational risks as only a part of supply chain risks to be identified and analysed.

[1] In this section the term 'supply chain risks' refers only to operational risks.

The remainder of this chapter introduces two frameworks for supply chain risk identification. The first framework is part of the literature review paper presented at the ANZAM 2014 conference (Section 2.2). The second framework is a reorganization of the first framework, and is presented in the paper about risk and resilience assessment in Section 2.3. Section 2.4 contains the outsourcing performance paper, and the chapter concludes with a summary in Section 2.5.

2.2. Paper 1: Operational risks categorization in supply chains[2]

Stream #16: Technology,
Innovation and Supply Chain Management

Competitive Session

Identifying drivers of supply chain vulnerability: An integrative framework

ABSTRACT: Supply chain risk management (SCRM) is an evolving field of research and practice. Considering the increasing fragmentation, and in some cases, dispersion of the SCRM literature in terms of identifying supply chain vulnerabilities, we seek to develop an integrative framework that unifies the global supply chain risk criteria scattered throughout the extant literature. Accordingly, we identify 58 key supply chain risk indicators and categorize them into 10 thematic groups. The constructs and measures included in this framework have been developed upon identifying and eliminating gaps in addressing a holistic risk identification framework in the most prominent scholarly literature on global SCRM.

Keywords: Supply chain risk management, risk identification, supply chain vulnerability, unified framework

Introduction

Since the beginning of the 21st century, managing risks in supply chains has become an increasingly critical topic, widely debated in both research and practice alike (Sodhi et al., 2012; Zsidisin & Wagner, 2010). There are many reasons behind the growing interest surrounding Supply Chain Risk Management (SCRM), including the globalization and ever-increasing outsourcing of manufacturing processes to countries with lower production costs and complex technological advancements (Christopher & Peck, 2004; Thun & Hoenig, 2011; Wagner & Bode, 2008; Wagner & Neshat, 2010), all contributing towards the increasing vulnerability of modern supply chains. Moreover, it has been

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[2] Pournader, M., Kach, A., Najmae,i A., & Keblis, M. (2014). *Identifying Drivers of Supply Chain Vulnerability: An Integrative Framework*. ANZAM Conference, Sydney, NSW, Dec. 2014 (Oral presentation-Competitive Session).

argued over the past few years that the severity and frequency of supply chain disruptions has been steadily on the rise (Craighead et al., 2007; Ritchie & Brindley, 2007). According to the annual 'Supply Chain Resilience 2013' report conducted by the UK Business Continuity Institute (Glendon & Bird, 2013b), 75% of the respondents were affected by at least one source of supply chain risk and 15% experienced loss of more than one million Pounds in 2012-2013. There are also numerous cases of vulnerabilities in supply chains that culminated in significant losses over the past years (e.g., Blackhurst et al., 2008; Jüttner, 2005; Rao & Goldsby, 2009a). Therefore, identification of the full spectrum of supply chain risks is vital for assuring transparency among supply chain partners, thereby providing an effective tool for supply chain vulnerability (SCV) evaluation.

Despite the attempts to develop a risk identification framework capable of categorizing the abundant yet scattered supply chain risk factors, prior approaches focus on either upstream or downstream risks in supply chains (e.g., Wu, Blackhurst, & Chidambaram, 2006; Zsidisin & Smith, 2005) or provide a limited view of the overall impending risks that global supply chains might encounter (e.g., Bogataj & Bogataj, 2007; Kleindorfer & Saad, 2005). Additionally, in their attempt to discern research gaps in the realm of SCRM, Sodhi et al. (2012, p. 9) state the need for 'defining the spectrum of types of supply chain risks that require responses' in order to reveal hidden aspects of risks in SCRM frameworks. Overall, despite a number of recent efforts towards building a unified supply chain vulnerability identification framework, there has been little consensus among researchers on the fundamental principles of designing such framework (Sodhi et al., 2012; Tang & Musa, 2011).

In light of the above, the main objective of this paper is to review the extant literature in order to design a unified framework for identifying the sources of supply chain vulnerability. This framework can contribute towards advancing theory and practice in the growing field of SCRM.

The rest of the paper is organized as follows. Next, we review the SCRM literature to render a holistic review of the main risk identification frameworks debated so far by the researchers. After investigating the gaps in the literature, we then present a unified SCV framework and discuss the main features of its risk constructs and risk measures.

Finally, we conclude by illuminating several directions for future studies in the SCRM area considering the recent trends including sustainability practices in supply chains.

Risk identification and categorization in the literature

Our approach in developing the unified SCV framework is that we initially looked for risk identification frameworks of global supply chains presented in all the relevant SCRM articles and published between 2000-2014 in top-tier journals in Operations and Supply Chain Management. The publications considered for this purpose are mainly ranked A and A* journals in the ABDC list. We further narrowed the literature to the most cited frameworks for our SCV framework in order to maximize construct validity and achieve parsimony. Table 2.1 reveals the outcome of these efforts.

Table 2.1 Review of the literature on SCV drivers

Author(s)/Year	Book/Journal title	Main Aspects of the Framework
Jüttner et al. (2003)	International Journal of Logistics Research and Applications	Environmental risks Network risks Organizational risks
Christopher and Peck (2004)	The International Journal of Logistics Management	Internal to the firm (Process and control risks) External to the firm but internal to the supply chain network (Demand and supply risk) External to the network (Environmental risk)
Spekman and Davis (2004a)	International Journal of Physical Distribution and Logistics Management	Risks associated with the flows of material, information, and cash Risks associated with security Risks associated with opportunistic behaviour Risks associated with corporate social responsibility
Chopra and Sodhi (2004)	MIT Sloan Management Review	Disruptions Delays Systems Forecast Intellectual Property Procurement Receivables Inventory Capacity

Author(s)/Year	Book/Journal title	Main Aspects of the Framework
Hallikas et al. (2004a)	International Journal of Production Economics	Demand risks Customer-delivery risks Cost and pricing risks Resources-specific risks Development-specific risks Flexibility-specific risks
Peck (2005)	International Journal of Physical Distribution and Logistics Management	Product/process risks Assets/infrastructure risks Risks associated with organizations and inter-organizational networks Environmental risks
Kleindorfer and Saad (2005)	Production and Operations Management	Operational contingencies Natural hazards earthquakes, hurricanes, and storms Terrorism and political instability
Wagner and Bode (2006)	Journal of Purchasing and Supply Management	Demand-side risks Supply-side risks Catastrophic risks
Wu et al. (2006)	Computers in Industry	Internal controllable risks Internal partially controllable risks Internal uncontrollable risks External controllable risks External partially controllable risks External uncontrollable risks
Bogataj and Bogataj (2007)	International Journal of Production Economics	Supply risk Process, production, or distribution risk Demand risk Control risk Environmental risk
Ritchie and Brindley (2007)	An emergent framework for supply chain risk management and performance measurement	Risks specific to external environment Industry-specific risks Risks specific to supply chain configuration Partner-specific risks Node-specific risks
Wagner and Bode (2008)	Journal of Business Logistics	Demand-side risks Supply-side risks Regulatory, legal and bureaucratic risks Infrastructure risks Catastrophic risks

Author(s)/Year	Book/Journal title	Main Aspects of the Framework	
Manuj and Mentzer (2008b)	Journal of Business Logistics	Supply Risks Demand Risks Macro Risks Competitive Risks	Operational Risks Security Risks Policy Risks Resource Risks
Manuj and Mentzer (2008b)	International Journal of Physical Distribution and Logistics Management	Supply risks Operational risks Security Risks	Demand risks Currency risks
Tang and Tomlin (2008)	International Journal of Production Economics	Supply risks Demand risks risks Behavioural risks	Process risks Intellectual property Political/social risks
Rao and Goldsby (2009a)	International Journal of Logistics Management	Framework risks Problem-specific risks Decision making risks	
Trkman and McCormack (2009)	International Journal of Production Economics	Exogenous risks Endogenous risks	
Tang and Tomlin (2009a)	Supply Chain Risk	Supply risks Demand risks Disruption Risks Intellectual property risks Political risks	Process risks Rare-but-Severe Behavioural risks Social risks
Wagner and Neshat (2010)	International Journal of Production Economics	Demand-side risks Supply-side risks Structural risks	
Christopher et al. (2011)	Supply Chain Management: An International Journal	Supply risk Environmental and sustainability risk Process and control risk Demand risk	
(Thun and Hoenig (2011))	International Journal of Production Economics	External supply chain risks Internal supply chain risks	
(Tummala and Schoenherr (2011))	Supply Chain Management: An International Journal	Demand risks Disruption risks breakdown risks Inventory Risks Supply risks Sovereign risks	Delay risks Manufacturing Physical plant risks System risks Transportation risks

According to Table 2.1, Chopra and Sodhi (2004) in their acknowledged framework of global supply chain risks identification discuss nine distinct risk categories. By presenting a holistic review of risks in supply chains, they suggest it could help towards 'proactively managing' disruptions, hence reducing the vulnerability of supply chains that could cost the embedded companies millions of dollars. Despite their attempts to capture the main risks triggering supply chain disruptions, the nature of 'relations' between supply chain members has been overlooked. Opportunistic behaviour of suppliers (Hallikas, Karvonen, Pulkkinen, Virolainen, & Tuominen, 2004a; Hallikas, Virolainen, & Tuominen, 2002a; Spekman & Davis, 2004a) or changes in the preferences of customers (Sodhi & Lee, 2007) are few examples that indicate the shortcomings of the framework designed by Chopra and Sodhi (2004). In another categorization of global supply chains risks, Kleindorfer and Saad (2005) suggest operational risks, natural hazards, and social and political instabilities as the main causes of disruptions in supply chains. However, they do not incorporate supply and demand risks in their final conceptual model for risk mitigation and management purposes.

Looking at more recent articles that present risk identification frameworks, Thun and Hoenig (2011) overlook the effects of inventory risks such as 'bullwhip effect' (Lee, 1997; Manuj & Mentzer, 2008b; Sodhi & Lee, 2007) or financial risks of supply chain members (Christopher & Peck, 2004; Tang & Musa, 2011) to name just a few. Additionally, despite the fact that Tummala and Schoenherr (2011) cover the inventory risks in their rather comprehensive supply chain risk framework, they fail to take volatilities in market and customer behaviour (Van der Vorst & Beulens, 2002; Wu et al., 2006) or financial risks of supply chain members into consideration.

Considering the limitations of the existing frameworks to come up with a comprehensive model of supply chain risks, we attempt to present a unified SCV framework that could address the highlighted shortcomings and offer a more comprehensive picture of the antecedents of vulnerabilities in supply chains.

The proposed framework

Methodology

Adopting systematic approach to the review of the literature creates a firm foundation for advancing knowledge (Webster & Watson, 2002). An integrative review is a systematic approach that '… synthesizes representative literature on a topic in an integrated way such that new frameworks and perspectives on the topic are generated' (Torraco, 2005, p. 356). Following this logic, we applied the integrative approach proposed by Torraco (2005) and extended by (Yorks, 2008) to develop a new framework for identifying and classifying risks in supply chain management literature. First, we asked the questions of is there a need for an integrative review, and if so, what type of review is necessary? Having identified the gap in the existing literature, the type of review was chosen to be taxonomical or conceptual classification of constructs. This type is suitable when the study is aimed '… to classify previous research…' and subsequently to '… lay the foundation for new theorizing' (Torraco, 2005, p. 363). Next, we selected the representative literature by defining qualifying criteria, i.e., supply chain risk frameworks published from 2000 to 2014 in the ABDC list of A and A* journals. Boundaries of the field were defined by organizing the review around a coherent conceptual structuring of the topic specified by the first and second author and agreed upon by the third and fourth author. Finally, the style of synthesis and write up was set to represent a taxonomy that transcends the current frameworks and is capable to inspire future research to converge into a more fine-grained direction.

To sum up, the proposed SCV framework is derived from 97 articles published in top 20 journals in the field of Operations and Supply Chain Management. Our analysis reveals 58 risk factors (i.e., risk measures) in 10 thematic groups as illustrated in Table 2.2. The process of classifying risk indicators into larger groups was conducted by the first and second authors to achieve inter-coder agreement and discussed with the third and fourth authors to achieve a satisfactory level of internal consistency and construct validity.

Table 2.2 The proposed unified SCV framework

Risk Constructs	Risk Measures
Customer behaviour	*Increasing bargaining power of customers*
	Variation of customer preferences
	Uncertain payment behaviour of customers
	Customer independency on products and services
	Low confidence level towards products and services
	Low profit margin gained from customers
Distribution-Transportation	*Additional transportation costs caused by technical malfunctions*
	Fuel price fluctuations
	Cargo losses/damages/delays/thefts
	Financial failures of distributors/transport providers
	Faulty product consignments
Economic-Financial	*Unfavourable macroeconomic conditions*
	Financial competitions [a]
	Financial disruptions [b]
	Excessively risky investment portfolio
	Low financial stability of suppliers/customers
	Excessive protectionism
External environment	*Health/safety risk*
	Man-made hazards
	Natural hazards
	Legal risks
Human resources	*Labour shortages*
	Labour turnover
	Rate and gravity of workplace (Management-Employee) conflicts
	Human and labour rights violation
	Low level of employee satisfaction
Information system	*Information flow insecurity*
	Unjustified investments on information systems
	Misuse of critical information
	Information distortion of supply tiers
	Insufficiency of real-time and updated information
	Obsolete information system and IT infrastructure

Risk Constructs	Risk Measures
Operational-Technical	*Technical breakdowns and process disruptions*
	Inflexible production system
	Infrastructure fragility
	Inefficient work/material/information flow
	Lack of technical innovation
	Loss of control over supply chain's processes
Quality	*Low product functionality*
	Low product reliability
	Low products durability
	Issues with products maintenance
	Low level of after-sale services
	Decreasing brand credibility
Quantity-Inventory	*Capacity fluctuations*
	Demand uncertainty
	Energy shortage
	Information shortage
	Supply shortage
	Inaccurate demand forecasts
Supplier-Partner relations	*Buyer-supplier communication problems*
	Intellectual property fraud
	Cultural differences
	Opportunistic tendencies of suppliers
	Insolvency (suppliers/partners)
	Loss of key suppliers/partners
	Low confidence level between supply chain partners
	Single sourcing

[a] *Price distinctions and lowering profit margins by competitors*
[b] *Loss of market share, stock value decrease, bankruptcy, and rise in labour cost*

Category 1: Customer behaviour

The volatility of customer preferences in a global market of products and services is known to be one of the main reasons behind SCV over the recent years (Braunscheidel

& Suresh, 2009; Peck, 2005; Sodhi & Lee, 2007). This has resulted in a strategic shift of modern organizations towards a better understanding and accounting for customer needs and market trends and towards assuring compatibility of supply chain processes (Wagner & Neshat, 2010; Zsidisin, 2003b). On the other hand, globalization and the emergence of new competitive markets are among the main reasons behind the increase in the bargaining power of customers (Finch, 2004). For example, customers nowadays are more prone to shifting from one manufacturer or service provider to another if not satisfied with the quality of products and/or the level of customer care (Hallikas et al., 2002a). Additionally, financial instability of customers is known to be another pivotal source of SCV, which might potentially cause adverse events including inability of customers to address contractual obligations, payment delays or debts (Wagner & Bode, 2009). Supply chains are exposed to this kind of risk both internally and externally. For instance, if a member of supply chain does not fulfil its financial obligations towards suppliers, this would cause an internal risk for suppliers and consequently for the overall supply chain. The same could happen if the customers in the market are not willing or able to buy the final products of supply chain.

Category 2: Distribution-Transportation

Flawless distribution and transportation performance may have a significant share in supply chain cost savings (Gunasekaran, Patel, & McGaughey, 2004; Zsidisin, Ellram, Carter, & Cavinato, 2004a). A number of articles in the SCRM literature discuss the adverse events that result in logistics inefficiencies including: delivery failures such as cargo losses (Blos, Quaddus, Wee, & Watanabe, 2009; Spekman & Davis, 2004a), incidents such as theft or vehicle crashes (Norrman & Jansson, 2004), delays (Zsidisin, 2003b), improper logistics planning and technical problems that cause additional transportation costs (Zsidisin et al., 2004a), and finally 'flawed consignments' (Jüttner & Ziegenbein, 2009, p. 205). Moreover, the transportation costs, which are the primary concern of distributors, are directly affected by energy prices (Asbjørnslett, 2009; Klibi & Martel, 2012).

Category 3: Economic-Financial

Financial risks and economic instability have received considerable attention in SCRM literature (few references). More specifically, researchers have discussed currency fluctuations (Christopher, Mena, Khan, & Yurt, 2011; Sodhi & Lee, 2007; Zsidisin, 2003b; Zsidisin et al., 2004a), inflation (Burtonshaw-Gunn, 2009; Manuj & Mentzer, 2008b), and recession (Blos et al., 2009) as some influential factors that could affect the performance of supply chain members and pose risks to the management of supply chains.

Additionally, well established and powerful newcomers in the market might bring a number of economic and financial threats such as an increased degree of competition by lowering their profit margins, superior customer relationship solutions, and other strategic advantages (Sodhi & Lee, 2007; Wagner & Bode, 2008). The next decisive criterion in this risk group relates to financial disruptions, including bankruptcy (Schmitt & Singh, 2012; Wagner & Johnson, 2004), rise in labour and investment costs (Tang, 2006), and financial difficulties of suppliers or customers (Tang & Musa, 2011). Restraining international trade policies as a result of adoption of protective measures such as tariffs on important goods or protectionism by countries like China might lead to further instability of economic and financial markets (Bello, Lohtia, & Sangtani, 2004; Jiang, 2002).

Category 4: External environment

Environmental risks have been widely debated in the literature (e.g., Chopra & Sodhi, 2004; Christopher et al., 2011; Christopher & Peck, 2004; Sodhi & Lee, 2007). We categorize environmental hazards into two major groups of man-made and natural hazards. The man-made hazards are the threats that dispose supply chains to war, terrorism, sabotage, pollution, unrest, etc. (Chopra & Sodhi, 2004; Finch, 2004; Jüttner, 2005). Natural hazards, on the other hand are comprised of risks in which human actions are not included such as earthquake, epidemic/pandemic phenomena, flood, draught, tsunami, etc. (Norrman & Jansson, 2004; Rao & Goldsby, 2009a; Tummala & Schoenherr, 2011).

Additionally, constant changes in the social and political environment of a given country (Kleindorfer & Saad, 2005; Tang & Musa, 2011), regulatory obstacles (Christopher et al., 2011; Wagner & Bode, 2008), and bureaucracy (Autry & Sanders, 2009; Ponomarov & Holcomb, 2009) are the risk factors that also could have negative impacts on the performance of supply chains and scare away the investments that are required for sustained business growth in countries.

Category 5: Human resources

The review of the literature indicates that the risks related to human resources have been rather neglected in the frameworks for supply risk identification/evaluation. Jiang, Baker, and Frazier (2009) argue that supplier-labour problems might expose supply chains to three major risk type – that is, financial, operational and reputation risks. In the SCRM literature, Kleindorfer and Saad (2005, p. 53) imply to 'human-centred issues' such as 'strike' and 'fraud' for managing risks that are related to human resources. However, their focus is centred on man-made disasters which were earlier. Similarly, Chopra and Sodhi (2004, p. 54) consider 'labor dispute' in a general risk group of 'disruptions' along with other environmental risks such as 'natural disasters', 'war and terrorism', etc. Accordingly a large number of studies have considered limited aspects of this concept including 'labor strikes' or 'labor disputes' (Norrman & Jansson, 2004; Tummala & Schoenherr, 2011; Yang, Aydin, Babich, & Beil, 2009) without discussing the numerous causes of this event.

Moreover, firms' obligations towards their stakeholders and more specifically their employees through the prism of corporate social responsibility should not be overlooked (Basu & Palazzo, 2008; McWilliams & Siegel, 2001). Hence, in terms of risks associated with human resources in global supply chains, violation of labour and human rights could be considered as pivotal risk (Maloni & Brown, 2006). We therefore classified these factors as two general groups of causes (e.g., human rights violation, conflicts and dissatisfaction of employees) and effects (e.g., loss of key employees, labour shortages or turnovers).

Category 6: Information system

The primary consideration of major supply chains regarding the information systems is to procure necessary information for the effective operation of the supply chain and to maintain the confidentiality of information (Finch, 2004). Disruptions in information processing or breach of confidential of information in supply chains might be caused by several reasons such as information system breakdowns in more systematic networks or 'systems risk' (Sodhi & Lee, 2007, p. 1431) and disruptions in IT systems and security settings (Spekman & Davis, 2004a; Tang & Musa, 2011). Inappropriate use of shared information by supply chain members and the irresponsibility of firms to share necessary information in supply chains would constrain the knowledge sharing throughout the supply chain. Another major issue, which has been discussed in the context of information systems is the effect of information asymmetry (Bogataj & Bogataj, 2007; Tang, 2006) that subsequently causes the bullwhip phenomenon (Chopra & Sodhi, 2004; Matook, Lasch, & Tamaschke, 2009b) as discussed earlier. Overall, a secured and updated information system in supply chains could build mutual trust between supply members, nurture and reinforce a ground upon which they share information and knowledge, and thus leading to a better visibility of critical data in supply chains.

Category 7: Operational-Technical

Usually when some technical or operational errors occur for a specific supplier, the other dependent members of the supply chain on that specific supplier would also suffer the consequences (Jüttner, 2005). This could cause millions of dollars of losses in large companies or have detrimental effects for small firms (e.g., Norrman & Jansson, 2004; Sodhi et al., 2012). The operational disruptions are comprised of machinery breakdowns (Tummala & Schoenherr, 2011; Wagner & Bode, 2008) and technical problems in manufacturing processes, obsolete and fragile infrastructure, and material and work flow structure (Chopra & Sodhi, 2004). Identifying and applying technological advancements in supply chains (Matook et al., 2009b; Sodhi & Lee, 2007; Zsidisin, 2003b) are other sources of concern mainly in high-tech industries (Blos et al., 2009; Sodhi, 2005). Supply chains should be able to adopt the relevant technological solutions in order to assure flexibility when facing sudden changes (Hendricks & Singhal, 2005). Moreover, operational and technical inefficiencies of supply chains might result in additional costs, delays and further process breakdowns (Blos et al., 2009; Kleindorfer & Saad, 2005).

Category 8: Quality

The concept of 'Quality' in SCRM has not been heretofore sufficiently challenged by the researchers. Quality-related risks in the SCRM literature are considered merely as 'Quality problems' (Zsidisin, 2003a, p. 220), 'Poor quality or yield at supply source'

(Chopra & Sodhi, 2004, p. 54), or 'Supplier quality problems' (Wagner & Bode, 2006, p. 310).

Based on the supply chain quality management literature (e.g., Foster Jr, 2008; Lin, Chow, Madu, Kuei, & Pei Yu, 2005; Robinson & Malhotra, 2005), we define five critical measures for quality control of suppliers including functionality, reliability, efficiency, maintainability and profitability of goods and services that are the end results of supply chains. Certain standards should also be followed in every other aspect of the SCV framework. For instance increasing the functionality and efficiency of products needs a flawless operational and technical process. Consequently a qualified product is the final result of a qualified system that is behind controlling the system – that is, the supply chain. Supply chain quality management is comprised of numerous variables such as customer focus, quality practices, supplier relations, leadership, HR practices, business results, safety, and etc. (Foster Jr, 2008). In this study, we focus on more general measures to eliminate the complexity of the SCV framework.

Category 9: Quantity-Inventory

The main objective of mitigating this group of risk is to meet the customer demand An accurate projection of overall demand that is compatible with the actual demand and organizing a coordinated supply chain towards meeting these demands could be cost saving and beneficial for supply chains (Niranjan, Wagner, & Bode, 2011; Wagner & Bode, 2006). In order to meticulously plan for the quantity of products to be manufactured, supply chains need to have valid information of demands, their production capacity and inventory levels, otherwise excess or limited capacity could ultimately cause financial losses for the supply members (Hendricks & Singhal, 2005; Sodhi & Lee, 2007). The 'Quantity-Inventory' risk group deals with the prerequisites for production in supply chains. The first key necessity of production is 'material' that could be provided directly by market or by suppliers. On one hand, considering the short product life-cycle and the falling prices of the product in the market, excess inventory is the 'killer combination' for many companies (Chopra & Sodhi, 2004, p. 58). On the other hand, insufficient quantity of receivables either from market or suppliers could also have adverse outcomes on the manufacturing process while experiencing volatilities in demand (Peck, 2005). Inability to recognize the pipeline inventory is argued to be the main cause of over-ordering, shortage of inventory and dysfunctional behaviour in supply chains (Niranjan et al., 2011). In addition to the accurate information of demand and the supply chain performance, sufficient energy levels are also required and their shortages would be problematic for manufacturing.

Category 10: Supplier-Partner relations

The relations between members of a supply chain are the outcomes of how successfully managers could overcome risks in the other 9 risk groups. For example, communication problems in supply chains that are caused by an inefficient information system could result in other groups of risks such as excess or insufficient inventory (Christopher & Lee, 2004). Enabling collaboration in supply chains has been argued to facilitate improvements in performance and assure sustainability of the overall supply chain and distinct supply chain partners (Sahin & Robinson, 2002; Swink, Narasimhan, & Wang, 2007). (Angerhofer & Angelides, 2006, p. 283) position the objective of a collaborative supply chain as 'to gain competitive advantage, by improving overall performance through taking a holistic perspective of the supply chain'.

Despite an increasing number of studies that explore the success factors of supply chain collaboration, integration, and coordination as discussed above, the lack of trust between supply chain partners (Zsidisin & Ritchie, 2009) is a major issue, which subsequently might become the main cause behind opportunistic behaviour (Seiter, 2009; Spekman & Davis, 2004a) or violations in the intellectual property rights (Manuj & Mentzer, 2008b; Oke & Gopalakrishnan, 2009; Sodhi & Lee, 2007; Wagner & Bode, 2008) by members of global supply chains. On an opposite pole, buyer-supplier relationships can become ineffective due to the risks stemming from overconfidence in suppliers which in turn lean to actions such as the adoption of the single sourcing strategy (Thun & Hoenig, 2011; Wagner & Bode, 2006; Zsidisin et al., 2004a). Loss of key suppliers in this situation will automatically result in the interruption of key business processes potentially resulting in the financial and reputational damages due to breaking contractual obligations and inability to satisfy customer demand.

It is worth mentioning that not all the identified risk measures and constructs are evenly dispersed along supply chains and might affect operation in either upstream or downstream or both sides of supply chains with diversities in severity and frequency of occurrence. This could be considered as a subject for future research.

Discussion and conclusion

In this study we reviewed the extant literature since 2000 surrounding SCRM risk identification frameworks. After detecting and analysing the risk dimensions discussed within each article, we proposed a unified SCV framework comprised of 10 risk constructs and 58 risk measures. We shed light on areas that have been overlooked by previous scholars such as 'Quality', 'Human resources', and 'Supplier-partner relations' by tracing the risks associated with each area back to their roots and subsequently including those roots in the framework.

However, the unified SCV framework presented in this article is rather general and it requires delving deeper into some of the constructs and measures or adding or subtracting new risk sources. For instance, according to the rapidly growing field of sustainability in global supply chains , the 'External environment' risk construct could not be constrained to mere natural, legal, or human-related hazards that might affect supply chains, rather environmental impacts of supply chains such as their carbon footprints, product life cycle, production process, and etc. (Sarkis, 2003; Seuring & Mueller, 2008) should also be taken into consideration while planning for risk mitigation practices. Moreover, corporate social responsibility of global supply chains that we discussed earlier as part of risks associated with labour, is also concerned with a number of other factors including suppliers' social responsibilities, value creation for customers, fair trade, animal welfare, and etc. (Andersen & Skjoett-Larsen, 2009; Maloni & Brown, 2006).

Additionally, 'Supplier-partner relations' in supply networks might include a variety of risks, identified as manufacturing/service triads (Choi & Hong, 2002; Choi & Wu, 2009a; Li & Choi, 2009b), and has received increasing attention by the researchers for the past few years. In the context of triads, scholars discuss that risks emerged and propagated in supply networks are different in nature when triadic relations of buyer-supplier-customer, buyer-supplier-supplier, or buyer-supplier-supplier are studied as building blocks of supply networks. This could render the traditional risk identification processes in the SCRM field with a new network perspective instead of individualism.

Finally, it is strongly suggested that the future research investigate the interrelations of risk constructs that have been proposed in the SCV framework by conducting empirical researches. This might reveal invaluable insights into how diverse types of risk could instigate other risk groups and how intense is the impact of each of the risk constructs on supply chain resilience. The latter might also differ depending on the type of industry under investigation.

2.3. Paper 2: Operational risks and resilience assessment[3]

An analytical model for system-wide and tier-specific assessment of resilience to supply chain risks

Abstract

Purpose –Based on the emerging view of supply chains as complex adaptive systems, this study aims to build and test an analytical model for resilience assessment surrounding supply chain risks at the level of the supply chain system and its individual tiers.

Design/methodology/approach – To address the purpose of this study, a multimethod research approach is adopted as follows: first, data envelopment analysis (DEA) modelling and fuzzy set theory are used to build a fuzzy network DEA model to assess risk resilience of the overall supply chains and their individual tiers; next, the proposed model is tested using a survey of 150 middle- and top-level managers representing nine industry sectors in Iran.

Findings – The survey results show a substantial variation in resilience ratings between the overall supply chains characterizing nine industry sectors in Iran, and their individual tiers (upstream, downstream, and organizational processes). The findings indicate that the system-wide characteristic of resilience of the overall supply chain is not necessarily indicative of the resilience of its individual tiers.

Practical implications – High efficiency scores of a number of tiers forming a supply chain are shown to have only a limited effect on the overall efficiency score of the resulting supply chain. Overall, our research findings confirm the necessity of adopting both the system-wide and tier-specific approach by analysts and decision makers when assessing supply chain resilience. Integrated as part of risk response and mitigation process, the information obtained through such analytical approach ensures timely identification and mitigation of major sources of risk in the supply chains.

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[3] Pournader, M., Rotaru, K., Kach, A., & Razavi Hajiagha, S. H. (2016). An Analytical Model for System-wide and Tier-specific Assessment of Resilience to Supply Chain Risks. *Supply Chain Management: An International Journal (Rank A)*, *21*(5). (Published).

Originality/value – Supply chain resilience assessment models rarely consider resilience to risks at the level of individual supply chain tiers, focusing instead on the system-wide characteristics of supply chain resilience. The proposed analytical model allows for the assessment of supply chain resilience among individual tiers for a wide range of supply chain risks categorized as upstream, downstream, organizational, network, and external.

Keywords Supply chain risk, Resilience, Data envelopment analysis, Fuzzy set theory

Paper type Research paper

Introduction

The argument that supply chain disruptions are unavoidable, and as a consequence, that all supply chains are inherently risky (Craighead et al., 2007; Marley, Ward, & Hill, 2014) is becoming more relevant with each passing year. According to the annual Supply Chain Resilience Report issued by the UK Business Continuity Institute in 2012-2013 (cited in Glendon & Bird, 2013a), 75% of respondents, representing supply chains from 71 countries, experienced at least one major supply chain disruption. Moreover, in 15% of the reported cases such supply chain disruptions resulted in losses greater than one million GBP. Similarly, a series of global risk reviews issued by the United Nations and World Economic Forum for the past decade show an increase in number, adverse impact, and diversification of risks that countries and global businesses are exposed to (van der Vegt, Essens, Wahlström, & George, 2015). Such growth and diversification of risk exposures at a global scale has resulted in ever-increasing financial losses for global companies and supply chains (Matsuo, 2015; Rotaru, Wilkin, & Ceglowski, 2014; Sodhi et al., 2012). A recent study conducted by World Economic Forum and Accenture plc (World Economic Forum, 2013) indicates that supply chains encountering significant disruptions face an average share price reduction of 7%. Global propagation of the locally concentrated risks, which may lead to situations where global production is disrupted by a local event, and the reduction of risk visibility of monitoring systems due to the diversification of supply chains have been mentioned among key risk impacts towards modern supply chain management practices (World Economic Forum, 2013).

On a more extreme end of the scale, the repercussions of major natural and technological high-impact events is estimated in billions of dollars, and the recovery of the affected supply chains may take many months. Examples of this include the 2014 Typhoon Halong, South East Asia ($10+ billion, 41 weeks), flooding on Long Island, New York in 2014 ($4+ billion, 38 weeks), gas explosions in Kaoshing, Taiwan ($900+ million, 26 weeks), and the hazardous chemical spill in Arizona, US ($900+ million, 10 weeks) (Snell, 2015). In late October 2015, hurricane Patricia, the strongest hurricane ever recorded, hit the coast of southwestern Mexico (Samenow, 2015). At the time of the submission of this article, the impact of this disastrous event was not yet properly assessed. Overall, the number of events disruptive for supply chains ('supply chain bulletins') reported by The Resilinc EventWatch global supply chain event monitoring system more than doubled in 2015 compared with 2014, with a total of 741 supply chain bulletins published in 2015 versus 339 events reported in 2014 (Resilinc, 2015).

To effectively address the consequences of major adverse events that may lead to supply chain disruptions, the widely acclaimed industry frameworks, such as SCOR (APICS, 2012; Rotaru et al., 2014), and the approaches to supply chain risk management suggested in the academic literature have primarily focused on the activities associated with: early risk identification and assessment (Neiger, Rotaru, & Churilov, 2009), the development of resource-efficient risk response strategies, risk monitoring and communication (Chopra & Sodhi, 2004; Manuj & Mentzer, 2008a). At the same time, in light of the increasing complexity and vulnerability of the supply chains, a growing number of studies in the operations and supply chain literature have stressed the importance of conducting resilience assessments as part of routine supply chain risk management practices (Chopra & Sodhi, 2014; Sheffi & Rice Jr, 2005). The importance of resilience, when dealing with unforeseen risks and assuring continuity of critical processes, has been reported by Sheffi and Rice Jr (2005) and Ambulkar et al. (2015).

Identifying main sources of risk and developing subsequent capabilities to appropriately compensate for risk exposures are critical factors contributing towards supply chain resilience and continuity of the core supply chain processes (Pettit, Croxton, & Fiksel, 2013; Pettit, Fiksel, & Croxton, 2010). At the same time, empirically-validated resilience assessment models are still scarce in the supply chain literature. In this regard, the call for empirical research surrounding supply chain resilience made by (Jüttner & Maklan, 2011, p. 255) to "…identify which supply chain capabilities can support the containment of the risk consequences and how these capabilities can be supported by effective SCRM [Supply Chain Risk Management]" is still relevant today.

While a single overarching definition of resilience has not yet been adopted in the supply chain literature, multiple studies investigating this construct generally view it as the ability of the supply chain to anticipate internal and external shocks, efficiently respond to the realised disruptive events, and maintain the continuity of its core business functions given the uncertainty of the environment in which modern supply chains operate (Day, 2013; Heckmann, Comes, & Nickel, 2015; Ponomarov & Holcomb, 2009; Reyes Levalle & Nof, 2015). Considering the design of the modern supply chains (APICS, 2012), resilience has been described as the product of complex interplay between supply chain members, which implies a close relationship between changes in tier-specific resilience levels of the supply chain and resilience levels of other supply chain members (Pereira et al., 2014). Such effects have a tendency to propagate to the level of the whole supply chain system (van der Vegt et al., 2015). At the same time, merely focusing on increasing resilience among components (i.e., supply chain tiers) of a complex supply chain system does not guarantee the overall resilience of the system under investigation (van der Vegt et al., 2015).

To date, the literature examining the relationship between risk exposures and resilience in supply chains has primarily reported on supply chain resilience from a system-wide supply chain perspective (Ambulkar et al., 2015; Brandon-Jones, Squire, Autry, & Petersen, 2014; Jüttner & Maklan, 2011). Although such an approach provides a unified view on the resilience associated with the given supply chain, it offers limited understanding on how the resilience level of individual supply chain members affects the resilience of the overall supply chain. Considering the fact that the resilience of the overall supply chain can only be improved or deteriorated through supply chain partners' individual contributions, the ability to conduct resilience assessment at the level of individual supply chain partners (considered as individual tiers of the supply chain system) as well as at the level of the supply chain overall is relevant to both theory and practice.

This study aims to address the need for a resilience assessment approach allowing practitioners and scholars to measure resilience to supply chain risk at the level of the overall supply chain system and its individual tiers. In doing so, the study follows the core tenets of the emerging theory of the supply chain (Carter et al., 2015), and specifically the view of the supply chain as a complex adaptive system (Choi & Hong, 2002; Hearnshaw & Wilson, 2013; Nair et al., 2009). Seen from this perspective, the "behaviour [of the supply chain system] ... is induced not by a single entity but rather by the simultaneous and parallel actions of agents within the system itself" (Choi, Dooley, & Rungtusanatham, 2001, p. 354). In the supply chain resilience literature, the view of the supply chain as complex adaptive system has been adopted by Surana, Kumara *, Greaves, and Raghavan (2005) who studied a variety of complex network topologies emphasising the importance of resilience as a critical factor for assuring supply chain performance. To address the aforementioned research need, a model built using the network data envelopment analysis (DEA) modelling approach (Fare & Grosskopf, 2000; Fare, Grosskopf, & Brännlund, 1996) and fuzzy set theory (Zadeh, 1965) is proposed. The suggested fuzzy network DEA model allows to: (i) account for uncertainties associated with risk and resilience levels in the given supply chains, (ii) assess supply chain resilience to the identified risks at the level of the overall supply chain and its individual tiers, and (iii) rank supply chains based on their level of resilience to risk. To the best of our knowledge, this study is the first to introduce the application of network DEA modelling to facilitate the assessment of supply chain resilience to risks.

Overall, our approach contributes to the emerging body of literature by emphasising the importance of bringing together an integrative and quantifiable 'pre-disruption' model of supply chain resilience, such as risk preparedness, risk mitigation, and 'post-disruption' aspects of this notion which relate to recovery and stabilization of supply chains once the disruptive event has been realised (Ivanov, Sokolov, & Dolgui, 2014; Leat & Revoredo-Giha, 2013; Reyes Levalle & Nof, 2015). For instance, the methodological solution suggested in our study supports practical implementation of the recommendation made by Leat and Revoredo-Giha (2013, p. 227) for "synthesising a balanced vulnerability to risks with risk management capabilities". Our specific contribution to this literature is a clear quantifiable delineation of resilience assessment at the level of individual supply chain members and supply chain as an overall system, since the assessment of the resilience levels of the distinct components of the supply chain does not give an indicative result for the resilience level of the overall SC system.

Lastly, our approach allows for the identification of which supply chain components/tiers under investigation need specific attention in order to improve the overall resilience level of the supply chain system.

The suggested model is tested using a survey comprised of 150 mid- and top-level managers representing nine main industries in Iran. Based on the survey responses, risks and resilience ratings for the overall supply chains associated with these industries, as well as for the individual tiers of these supply chains are evaluated and ranked. The results allow for insight into the resilience to risk ratings within each industry, and subsequently, where potential improvements can be made.

The remainder of this study is organized as follows. The *Background* section provides an overview of the systems perspective on supply chain risk and resilience, the link between the notions of risk and resilience, and the application of DEA and network DEA for the assessment of resilience to supply chain risks. Next, the *Analytical Model* section outlines the network DEA model for resilience assessment suggested in this study. The following section reports on the results of the survey study conducted to test the suggested network DEA model for resilience assessment. The paper concludes by outlining some limitations associated with this study and by suggesting a number of possible extensions based on the presented results.

Background

Systems view of risk and resilience in supply chains

The recent study by Carter et al. (2015) on the emerging theory of the supply chain conceptualizes supply chains as: (i) networks consisting of focal organizations that are linked to upstream and downstream partners; and (ii) complex adaptive systems, which exhibit properties such as self-organization, emergence and limited visibility of individual partners. This view suggests that all members of a supply chain can be viewed as self-organizing adaptive agents whose individual behaviour is interdependent and affects the whole system (Choi & Hong, 2002; Nair et al., 2009). For example, a three-tier supply chain that consists of upstream, downstream, and organizational processes, exhibits unique characteristics, or emergent properties, which are not properties of its distinct processes but the whole supply chain (Day, 2013). Carter et al. (2015, p. 90) explain this property as follows: "An agent as a node in a supply chain can look upstream toward its suppliers or downstream toward its customers. However, the visibility in either direction is invariably going to be limited. What lies beyond the realm of its visible range simply *emerges* for this agent". This view implies inherent differences in the risk profile of a supply chain as a whole when compared to the sum of risk profiles associated with its individual tiers due to the limited risk visibility of each tier within the supply chain. Taking this into consideration, individual supply chain partners and their inter- and cross-organizational processes affect the behaviour of the overall supply chain system. Summarizing the above, in the context of three-tier supply chains, new risk types emerge, which do not encapsulate the inherent properties of the distinct tiers but are instead products of the relationships between all components of the supply chain. Hence, the assessment of the susceptibility of supply chains to a variety of risks requires both a component-specific analysis that considers risks in individual supply chain tiers and a systems-level perspective dealing with risks that emerge as a product of interrelations between the tiers.

Resilience and the typology of the supply chain risk sources

Definition and assessment of supply chain resilience

The term resilience generally infers the ability to address and accommodate abnormal events and threats that may potentially result in the disruption of the critical processes within supply chain (Day, 2013; Heckmann et al., 2015). There is no unique definition of resilience unanimously agreed upon in the supply chain literature. Taking into consideration a number of established and emerging definitions of supply chain resilience (Kim, Chen, & Linderman, 2015; Zhao, Kumar, Harrison, & Yen, 2011) in this study we adopt an integrative view of the supply chain resilience which combines 'pre-disruption' and 'post-disruption' components of this notion (e.g., Ivanov et al., 2014). In particular, we see the following two definitions of resilience as the most appropriate for our study:

- Ponomarov and Holcomb (2009, p. 131) view of supply chain resilience as "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" ; and

- Reyes Levalle and Nof (2015, p. 83) view of resilience within supply network (SN) as "the inherent ability of a SN agent and/or the emergent capability of a SN to (i) anticipate errors and conflicts; (ii) prevent them from creating disruptions to normal operation, and (iii) overcome disruptions within minimum QoS [quality of service] loss, within sustainable use of resources".

A number of recent studies (e.g., Hohenstein, Feisel, Hartmann, & Giunipero, 2015; Kamalahmadi & Parast, 2016; Tukamuhabwa, Stevenson, Busby, & Zorzini, 2015) provide a systematic review of prior literature on supply chain resilience, existing definitions and properties which form this complex construct. While proactive identification and response to supply chain risks is highly desirable (Neiger et al., 2009), the uncertainty associated with today's global supply chain environment (Resilinc, 2015) dictates the need for preparedness and effective response to major disruptive events (Hasani & Khosrojerdi, 2016; Kamalahmadi & Parast, 2016). The latter is associated with the ability of each given supply chain to effectively identify at an early stage the potential impact of a disruptive event and implement a relevant mitigation strategy considering the possible impact of each given event as a function of time since the event occurred, as well as the costs of mitigation strategies (Nooraie & Parast, 2016).

In view of the above, supply chain resilience assessment aims at improving the capability of the supply chain system to prepare for, respond to and recover from the consequences of realised risks (Ponomarov & Holcomb, 2009). Considering that not all sources of risks could be prevented from occurrence (Jüttner & Maklan, 2011) and that there is often times scarcity of statistical information surrounding frequency and probability of risk exposures and disruptions (Fiksel, Polyviou, Croxton, & Pettit, 2015), it can be said that the traditional supply chain risk management approach that emphasizes the importance of preventive risk identification and response (Neiger et al., 2009) is only partially capable to protect supply chains from the harms of disruptions (i.e., to the extent when potential disruptive events are predictable and may be efficiently mitigated in a proactive manner). This calls for an aggregated view that enables proactive identification and assessment of supply chain risks and assures a high level of supply chain resilience. Moreover, issues surrounding supply chain risk exposures imply a direct relationship between the resilience of supply chains and the ability of organizations forming supply chains to assess current risk exposures and recover from disruptions when risks turn into realised events and subsequent losses (Christopher & Peck, 2004; Sheffi & Rice Jr, 2005; Waters, 2011).

Properties of supply chain resilience

Readiness, *responsiveness*, and *recovery* (Sheffi & Rice Jr, 2005) have been identified as formative properties of supply chain resilience and have been studied at both resource-specified level (Sheffi, 2005) and system-wide supply chain level (Christopher & Peck, 2004). This list has been extended by Ponomarov and Holcomb (2009) and Jüttner and Maklan (2011) who also suggested *flexibility*, *velocity*, *visibility*, and *collaboration* as properties reflecting the capability of a given supply chain to assure a desirable level of resilience in face of possible disruptive events. A more detailed discussion of the aforementioned properties of supply chain resilience can be found in Jüttner and Maklan (2011).

Apart from the prescriptive literature in the area of supply chain resilience, outlined above, several empirical studies have been conducted with the view to identify the core properties of supply chain resilience seeing those properties associated with supply chain resilience. Based on systems theory and resource-based view of individual firms forming supply chains, Blackhurst, Dunn, and Craighead (2011) proposed a framework for assessing the resilience of the supply base. They identify and discuss how resilience in supply chains could be improved. Ambulkar et al. (2015) investigated supply chain resilience through the prism of *supply chain disruption orientation*, *firm's resource reconfiguration capabilities* and *firm's risk management infrastructure* when dealing with high impact or low impact disruptions. Their study makes an explicit connection between supply chain risk exposures and the strategies to enhance supply chain resilience. Our study follows this avenue of researching the phenomenon of supply chain resilience by emphasising the importance of identifying and assessing the main sources of risks in supply chains and, based on this understanding, develop relevant strategies for enabling supply chain resilience.

Another necessary condition for developing a resilient supply chain is the visibility of *risk sources* within a given supply chain (Pettit et al., 2013; Pettit et al., 2010). A variety of frameworks for supply chain risk identification have been suggested (see Rao & Goldsby, 2009b; Sodhi et al., 2012; Sodhi & Tang, 2012c). The supply chain risk model proposed in our study incorporates both recurrent and disruptive risks. Disruptive risks are less frequent, independent of supply chain practices, and have more substantial effects on supply chain processes compared to recurrent risks (Chopra & Sodhi, 2014). Our focus is on a three-tier supply chain, which comprises a supplier, a manufacturer and a distributor, their organizational processes, and the upstream, and downstream processes that provide cross-organizational linkages between the partners of the supply chain.

Typology of supply chain risk sources

In terms of risks associated with 'upstream' supply chain processes, 'single sourcing', or an excessive dependency on a single source of supply, has been reported as a major obstacle in attaining supply chain resilience (Hendricks & Singhal, 2005; Tummala & Schoenherr, 2011). Opportunistic behaviour (Hallikas, Virolainen, & Tuominen, 2002b; Peck, 2005) and inadequate responsiveness of suppliers to changes in demand, technological changes, and new rules and regulations (Wagner & Neshat, 2010; Zsidisin & Ellram, 2003) have been reported as other sources of upstream risks. Operational inefficiencies of suppliers in terms of quality issues (Matook, Lasch, & Tamaschke, 2009a; Thun & Hoenig, 2011; Zsidisin, Ellram, Carter, & Cavinato, 2004b), poor performance in logistics (Wagner & Bode, 2006; Wagner & Neshat, 2012), and financial instability (e.g., bankruptcy, default, insolvency) of supplier(s) (Hua, Sun, & Xu, 2011; Wagner & Johnson, 2004) constitute other sources of risks in upstream supply chains. We recommend Colicchia, Dallari, and Melacini (2010) for a more comprehensive overview of risks associated with the inbound processes.

Risks associated with 'organizational' processes in supply chains are mainly observed as infrastructure breakdowns (e.g., IT system failure or machine breakdown) (Jüttner et al., 2003; Wagner & Bode, 2008), safety and quality issues (Manuj & Mentzer, 2008c; Tang & Tomlin, 2009b), unanticipated changes in the design of products (Ghadge, Dani, Chester, & Kalawsky, 2013; Tummala & Schoenherr, 2011), issues with human resources (e.g., disputes, strikes, and civil unrest) (Chopra, Lovejoy, & Yano, 2004;

Spekman & Davis, 2004b), financial, inventory and capacity inflexibilities (Cachon, 2004; Chopra & Sodhi, 2004; Sodhi, 2005).

Next, 'downstream' supply chain risks are mainly related to volatile customer demand (Spekman & Davis, 2004b; Wagner & Bode, 2006), transportation (Chopra & Sodhi, 2004; Wagner & Bode, 2008) and assignment of products to customers (Cavinato, 2004; Hallikas, Karvonen, Pulkkinen, Virolainen, & Tuominen, 2004b). In addition to the aforementioned three main risk types pertinent to each tier of the supplier-manufacturer-distributor supply chains, two additional risk types may be considered: risks associated with the supply chain as a whole, and risks associated to the external events, i.e., those which come from outside of the supply chain system.

The emerging theory of the supply chain (Carter et al., 2015) conceptualizes supply chains as networks consisting of focal organizations that are linked to upstream and downstream partners. The organizations forming the nodes of such network can be viewed as adaptive agents that may affect each other and the whole system. The interconnectedness between the nodes of the supply network may lead to scenarios when risks (referred to as 'network' risks here) originating within a specific node of the supply network can propagate to other nodes of the supply network (Ghadge et al., 2012; Sodhi & Tang, 2012a). The reported factors contributing toward the emergence of these risks include lack of trust and/or low levels of supply chain visibility among supply chain members (Tang & Tomlin, 2008). 'Bullwhip effect'(Lee, 1997; Lee, Padmanabhan, & Whang, 2004) is a well-known model describing the causes and consequences of network type risk scenarios when limited information sharing in the supply chain results in over- or underestimation of demand. In the absence of proper preventive controls, the issue commonly results in loss of income, extra inventory costs or product obsolescence (Disney & Towill, 2003a, 2003b; Towill, 2005). 'External' risks are caused by threats of an external environment (i.e., factors outside the boundaries of a supply chain), including man-made (e.g., terrorist, changes in regulatory systems, attacks, theft, war) or natural (e.g., natural disasters, weather extremes, diseases and epidemics) hazards that may severely disrupt supply chain operations (Ghadge et al., 2012; Jüttner, 2005).

Application of DEA and network DEA for assessment of resilience to supply chain risks

DEA and Network DEA method

Another issue addressed in this study is the lack of research guiding the assessment of supply chain resilience to supply chain risks. A few attempts have been made so far to tackle this issue by developing analytical frameworks addressing the complex task of supply chain resilience assessment (Cabral, Grilo, & Cruz-Machado, 2012; Munoz & Dunbar, 2015; Pettit et al., 2013; Soni, Jain, & Kumar, 2014; Spiegler, Naim, & Wikner, 2012), while not focusing specifically on the pre-disruption phase of supply chain resilience (Ivanov et al., 2014) that includes risk assessment. The literature examining the relationship between risk exposures and resilience in supply chains has primarily reported on supply chain resilience from a system-wide supply chain perspective (Ambulkar et al., 2015; Brandon-Jones et al., 2014; Jüttner & Maklan, 2011), which contradicts the systems view of risks that requires both a system-wide and tier-specific assessment of supply chain resilience to risk exposures. This contributes to the lack of precision between reported inputs viewed in this case as the available statistical data on realised risks as well as the risk assessment data, and outputs presented as resilience assessment. In line with the research evidence summarized and reviewed by Hatami-Marbini, Emrouznejad, and Tavana (2011) such characteristic of inputs and outputs might require a necessary integration of fuzzy methods. To address the aforementioned issues, our study uses an analytical modelling approach grounded in Data Envelopment Analysis (DEA) and fuzzy network theory to incorporate the properties of supply chain resilience as well as risks threatening supply chains, and enable the comparison between resilience and risk ratios for multiple supply chains, considering the characteristics of the individual tiers and the whole supply chain systems.

DEA (Charnes, Cooper, & Rhodes, 1978) has been widely recognized as a method for performance measurement allowing to analyse simultaneously the performance, in its broadest sense, of several entities (e.g., supply chains and their individual tiers) based on multiple inputs and outputs. One of the main advantages of DEA over other analytical models is its ability to compare several entities with multiple inputs and multiple outputs with no pre-defined precise relations between input and output variables, which has made it applicable in a wide spectrum of real world contexts, including banking and hedge fund performance measurement and portfolio optimization (Gregoriou, Sedzro,

& Zhu, 2005; Liu, Lu, Lu, & Lin, 2013b). From the model building perspective, the application of DEA to assess hedge fund performance based on maximizing returns and minimizing risks, resembles the modelling problem addressed in our study that aims at ranking supply chains based on their performance in maximizing resilience and minimizing the effects of disruptions on the integrity and continuity of their operations.

Application of DEA and network DEA for supply chain resilience assessment

DEA has been adopted to evaluate and compare risk exposures of individual tiers in supply chains (see among Azadeh & Alem, 2010; Olson & Wu, 2011; Talluri, Kull, Yildiz, & Yoon, 2013; Talluri, Narasimhan, & Nair, 2006; Wu & Olson, 2008). Talluri et al. (2006) proposed a chance-constrained DEA (CCDEA) based on uncertain inputs and outputs to assess variations in vendor attributes in presence of supply risks. Azadeh and Alem (2010) developed DEA, fuzzy DEA and CCDEA models for supplier risk evaluation under uncertainty. Olson and Wu (2011) used DEA and Monte Carlo simulation for risk assessment in supply chains. They further tested their model to evaluate a variety of country-specific outsourcing strategies. More recently, Talluri et al. (2013) adopted a combination of simulation modelling and DEA to test the efficiency of risk mitigation strategies in 21 industries in the US.

While these models proved to be efficient for the assessment of supply chain risks, they do not directly address the task of supply chain resilience assessment. Furthermore, traditional DEA models are commonly described to resemble a 'black-box' (Fare & Grosskopf, 2000) in which the performance and the nature of the relationship between sub-processes of the system under investigation are overlooked. Such limitation is at odds with the call to enable supply chain resilience assessment at the level of individual supply chain partners and the supply chain system. Network DEA modelling (Fare & Grosskopf, 2000) is leveraged in this study to address the above concerns. Despite its advantages over more traditional types of DEA models and also its prevalence in a range of industrial and services sectors (Kao, 2014b; Moreno & Lozano, 2014; Yang & Liu, 2012), the application of network DEA in the context of supply chains has been limited (Chen & Yan, 2011; Mirhedayatian, Azadi, & Farzipoor Saen, 2014). To the best of our knowledge, this study is the first to introduce the application of network DEA modelling for the purposes of assessing supply chain resilience to risks.

Analytical model

In the previous sections of this study, we motivated our modelling approach by the need to combine the traditional view for identifying, managing and mitigating supply chain risks (Jüttner et al., 2003; Manuj & Mentzer, 2008a) with the supply chain resilience view, which corresponds to the readiness, responsiveness and recovery of supply chains from disruptions (Sheffi, 2005). Moreover, we stressed the lack of quantitative models for supply chain resilience assessment voiced in the literature (Hohenstein et al., 2015), let alone quantitative models that could incorporate both aspects of supply chain risk and resilience assessment. By acknowledging the existing studies that investigated supply chain resilience from solely the system-wide viewpoint (Ambulkar et al., 2015; Brandon-Jones et al., 2014; Jüttner & Maklan, 2011), we aim at developing an analytical model that could inform supply chain decision makers about the resilience to risk levels of the supply chains of interest at the tier-specific and system-wide levels of assessment.

To address the research aim above, our study adopts a multimethod research approach which allows us to design and test an analytical model for assessment of resilience to supply chain risk. First, DEA modelling and fuzzy set theory are adopted to develop an analytical model for risk and resilience assessment in a three-tier supply chain. As demonstrated in the following sub-sections, in the context of this study, DEA is capable to incorporate multiple risk and resilience measures as inputs and outputs to a supply chain system and enables the comparison between the current level of resilience to various supply chain risks with the desirable levels that supply chain decision makers aim to achieve. Additionally, network DEA makes these comparisons possible at both tier-specific (i.e., individual companies forming supply chains) and system-wide (supply chains as entities) levels of analysis.

Developed by Charnes et al. (1978), DEA measures the relative efficiency of a set of n decision making units (DMUs) that use m inputs to produce s outputs. Let X_{ij} denote the ith input, $i = 1, \dots, m$, and Y_{rj} the rth output, $r = 1, \dots, s$, for DMU j, $j = 1, \dots n$. Then the model for DMU_k originally presented by Charnes, Cooper, and Rhodes (CCR) (1978) can be formulated as follows:

$$E_k = max \sum_{r=1}^{s} u_r Y_{\mathrm{rk}} \bigg/ \sum_{i=1}^{m} v_i X_{\mathrm{ik}}$$

s.t.

$$\sum_{r=1}^{s} u_r Y_{rj} \bigg/ \sum_{i=1}^{m} v_i X_{ij} \leq 1, j = 1,2, \dots, n \tag{1}$$

$$u_r \geq \varepsilon > 0, r = 1,2, \dots, s$$

$$v_i \geq \varepsilon > 0, i = 1,2, \dots, m,$$

where ε is a small non-Archimedean value and u_r and v_i are virtual multipliers.

Model (1) can be transformed into an equivalent linear programming formulation (Charnes & Cooper, 1984):

$$E_k = max \sum_{r=1}^{s} u_r Y_{\mathrm{rk}}$$

s.t.

$$\sum_{i=1}^{m} v_i X_{\mathrm{ik}} = 1$$

$$\sum_{r=1}^{s} u_r Y_{\mathrm{rj}} - \sum_{i=1}^{m} v_i X_{\mathrm{ij}} \leq 0, j = 1,2, \dots, n \tag{2}$$

$$u_r \geq \varepsilon > 0, r = 1,2, \dots, s$$

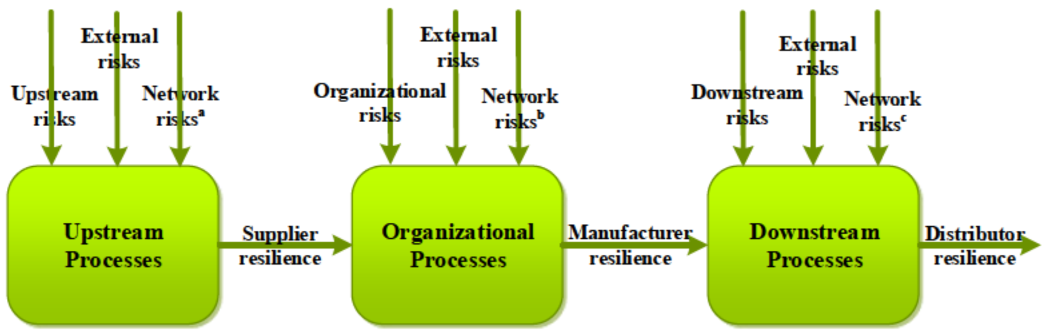
$$v_i \geq \varepsilon > 0, i = 1,2, \dots, m$$

Our study applies the suggested model for resilience assessment in the context of a three-tier supply chain, as outlined in Figure 2.1 and discussed below. Hence, model (2) is transformed into a network DEA model (Kao, 2014b; Kao & Hwang, 2008, 2010), which allows to capture risk and resilience factors in a three-tier supply chain. Moreover, network DEA is argued to have a greater discriminatory power than the conventional black-box model (Kao, 2014c), thus assuring the accuracy of the results obtained from the model. Model (2) is subsequently transformed to a fuzzy network DEA model thereby reflecting on uncertainties associated with risk data when the model is operationalized.

The network DEA model for evaluating supply chain resilience to supply chain risks

Figure 2.1 shows the proposed three-tier supply chain model including upstream, organizational, and downstream processes and their associated risk and resilience levels as inputs and outputs of inter- and cross-organizational processes. Potentially affecting all three tiers of the supply chain, risks can manifest in each process as disruptions to the operations, which form part of this process, and to the supply chain as a whole. Therefore, the more vulnerable a supply chain member (i.e., supplier, manufacturer, or distributor) is to risks (inputs), the less resilient are the operations of this member, (Jüttner & Maklan, 2011). Tier-specific resilience levels are portrayed as outputs to each process included in the model. If a certain tier (e.g., supplier) is susceptible to risks, the disruptions caused by those risks in a given tier could adversely affect subsequent tiers in the supply chain. For instance, if a supplier, due to being affected by an unexpected adverse event disrupting key business processes, cannot provide raw materials for the manufacturer in a timely manner, the effects of the disruptive event may propagate to manufacturer's operations (e.g., decreased production, excess backorder costs) (Garvey, Carnovale, & Yeniyurt, 2015). Hence, the resilience levels of upstream supply chain tiers, illustrated as outputs, could be considered as inputs to downstream supply chain tiers (Figure 2.1). According to Figure 2.1, upstream risks $(\tilde{X}_{11})$, external risks $(\tilde{X}_{12})$, network risks $(\tilde{X}_{13})$, are modelled as inputs to and supplier resilience $(\tilde{Z}_1)$ as intermediary output of the upstream processes, affecting suppliers' operations. Similarly, organizational risks $(\tilde{X}_{21})$, external risks $(\tilde{X}_{22})$, network risks $(\tilde{X}_{23})$ correspond to inputs, while manufacturer resilience $(\tilde{Z}_2)$ to the intermediary output for the organizational processes. Finally, downstream risks $(\tilde{X}_{31})$, external risks $(\tilde{X}_{32})$, network risks $(\tilde{X}_{33})$ represent inputs, and distributor resilience $(\tilde{Y}_3)$ is the output of the downstream processes. The '$\sim$' denotes risk and resilience levels as fuzzy values.

Figure 2.1 Proposed model for supply chain resilience assessment to risk exposures



[a]:Risks emerging as a result of supplier-manufacturer interactions and affecting upstream processes
[b]:Risks emerging as a result of manufacturer-supplier and manufacturer-distributor interactions and affecting organizational processes
[c]:Risks emerging as a result of distributor-manufacturer interactions and affecting downstream processes

The efficiency scores obtained from this model show the resilience/risk ratio used to compare their respective resilience toward supply chain risks. For each three-tier supply chain, modelled as a DMU, four different types of efficiency scores are proposed: the efficiency of upstream, organizational, and downstream processes, as well as the efficiency of the overall supply chain system. Following Kao and Hwang (2008), the efficiency of the overall supply chain, reflected in Figure 2.1 for DMU_k is formulated as follows:

$$\tilde{E}_k = max\ u_3 \tilde{Y}_3^k$$

s.t.

$$\sum_{t=1}^{3}\sum_{i=1}^{3} v_{ti}\tilde{X}_{ti}^k = 1 \qquad (3)$$

$$u_3\tilde{Y}_3^j - (\sum_{t=1}^{3}\sum_{i=1}^{3} v_{ti}\tilde{X}_{ti}^j) \leq 0, j = 1,2, \dots, n$$

$$w_1\tilde{Z}_1^j - \sum_{i=1}^{3} v_{1i}\tilde{X}_{1i}^j \leq 0, j = 1,2, \dots, n$$

$$w_2\tilde{Z}_2^j - (w_1\tilde{Z}_1^j + \sum_{i=1}^{3} v_{2i}\tilde{X}_{2i}^j) \leq 0, j = 1,2, \dots, n$$

$$u_3\tilde{Y}_3^0 - (w_2\tilde{Z}_2^j + \sum_{i=1}^{3} v_{3i}\tilde{X}_{3i}^j) \leq 0, j = 1,2, \dots, n$$

$$v_{ti}, u_3, w_1, w_2 \geq \varepsilon,$$

$$i = 1,2,3;\ t = 1,2,3,$$

where v_{ti} is the multiplier of ith input, $i = 1,2,3$, for the tth process, $t = 1,2,3$, and u_3 is the multiplier of the output for the third process. Also, w_1 and w_2 denote the multiplier of intermediate products in upstream processes and organizational processes, respectively.

Let v_{ti}^*, u_3^*, w_1^*, and w_2^* denote the optimal multipliers obtained from Model (3). The efficiency of each upstream, organizational, and downstream process for DMU_k is formulated as:

$$\tilde{E}_k^1 = w_1^*\tilde{Z}_1^k \Big/ \sum_{i=1}^{3} v_{1i}^*\tilde{X}_{1i}^k$$

$$\tilde{E}_k^2 = w_2^*\tilde{Z}_2^k \Big/ w_1^*\tilde{Z}_1^k + \sum_{i=1}^{3} v_{2i}^*\tilde{X}_{2i}^k \tag{4}$$

$$\tilde{E}_k^3 = u_3^*\tilde{Y}_3^k \Big/ w_2^*\tilde{Z}_2^k + \sum_{i=1}^{3} v_{3i}^*\tilde{X}_{3i}^k$$

Models (2-4) still are not capable to address the uncertainties associated with evaluation of risks and resilience in supply chains. Thus, Models (3-4) are transformed to by applying fuzzy sets to the risk data using α-cut approach.

Applying fuzzy sets and α-cut approach to the proposed network DEA model

Following Kao and Liu (2011), the α-cuts of inputs, outputs, and the intermediate products of the proposed model in Figure 2.1 for the triangular fuzzy numbers (TFNs) are as follows:

$$\begin{aligned}
(X_{11})_\alpha &= [(X_{11})_\alpha^L, (X_{11})_\alpha^U] = [(1-\alpha)X_{11}^1 + \alpha X_{11}^2, \alpha X_{11}^2 + (1-\alpha)X_{11}^3] \\
(X_{12})_\alpha &= [(X_{12})_\alpha^L, (X_{12})_\alpha^U] = [(1-\alpha)X_{12}^1 + \alpha X_{12}^2, \alpha X_{12}^2 + (1-\alpha)X_{12}^3] \\
(X_{13})_\alpha &= [(X_{13})_\alpha^L, (X_{13})_\alpha^U] = [(1-\alpha)X_{13}^1 + \alpha X_{13}^2, \alpha X_{13}^2 + (1-\alpha)X_{13}^3] \\
(X_{21})_\alpha &= [(X_{21})_\alpha^L, (X_{21})_\alpha^U] = [(1-\alpha)X_{21}^1 + \alpha X_{21}^2, \alpha X_{21}^2 + (1-\alpha)X_{21}^3] \\
(X_{22})_\alpha &= [(X_{22})_\alpha^L, (X_{22})_\alpha^U] = [(1-\alpha)X_{22}^1 + \alpha X_{22}^2, \alpha X_{22}^2 + (1-\alpha)X_{22}^3] \\
(X_{23})_\alpha &= [(X_{23})_\alpha^L, (X_{23})_\alpha^U] = [(1-\alpha)X_{23}^1 + \alpha X_{23}^2, \alpha X_{23}^2 + (1-\alpha)X_{23}^3] \\
(X_{31})_\alpha &= [(X_{31})_\alpha^L, (X_{31})_\alpha^U] = [(1-\alpha)X_{31}^1 + \alpha X_{31}^2, \alpha X_{31}^2 + (1-\alpha)X_{31}^3] \\
(X_{32})_\alpha &= [(X_{32})_\alpha^L, (X_{32})_\alpha^U] = [(1-\alpha)X_{32}^1 + \alpha X_{32}^2, \alpha X_{32}^2 + (1-\alpha)X_{32}^3] \\
(X_{33})_\alpha &= [(X_{33})_\alpha^L, (X_{33})_\alpha^U] = [(1-\alpha)X_{33}^1 + \alpha X_{33}^2, \alpha X_{33}^2 + (1-\alpha)X_{33}^3] \\
(Z_{1})_\alpha &= [(Z_{1})_\alpha^L, (Z_{1})_\alpha^U] = [(1-\alpha)Z_{1}^1 + \alpha Z_{1}^2, \alpha Z_{1}^2 + (1-\alpha)Z_{1}^3] \\
(Z_{2})_\alpha &= [(Z_{2})_\alpha^L, (Z_{2})_\alpha^U] = [(1-\alpha)Z_{2}^1 + \alpha Z_{2}^2, \alpha Z_{2}^2 + (1-\alpha)Z_{2}^3] \\
(Y_{3})_\alpha &= [(Y_{3})_\alpha^L, (Y_{3})_\alpha^U] = [(1-\alpha)Y_{3}^1 + \alpha Y_{3}^2, \alpha Y_{3}^2 + (1-\alpha)Y_{3}^3],
\end{aligned} \tag{5}$$

where, $\{(X_{11})_\alpha^L, 0 \le \alpha \le 1\}$ is the left-shape function and $\{(X_{11})_\alpha^U, 0 \le \alpha \le 1\}$ is the right-shape function of the membership function of $\tilde{X}_{11}$. The same explanation applies for the remaining equations in Model (5). Finding the membership function of the overall network efficiency for DMUk requires calculating the lower bound and upper bound of the α-cut of $\tilde{E}_k$, $(E_k)_\alpha = [(E_k)_\alpha^L, (E_k)_\alpha^U]$.

Built upon the models proposed by Kao and Liu (2000), Kao (2006) and Kao and Liu (2011) Model (3) transforms to the following Model (6) for DMU_0:

$$(E_k)_\alpha^U = max\, u_3(Y_3^k)_\alpha^U$$

s.t.

$$\sum_{t=1}^{3}\sum_{i=1}^{3} v_{ti}(X_{ti}^k)_\alpha^L = 1$$

$$u_3(Y_3^k)_\alpha^L - \left(\sum_{t=1}^{3}\sum_{i=1}^{3} v_{ti}(X_{ti}^k)_\alpha^U\right) \le 0$$

$$u_3(Y_3^j)_\alpha^L - \left(\sum_{t=1}^{3}\sum_{i=1}^{3} v_{ti}(X_{ti}^j)_\alpha^U\right) \le 0, j = 1,2,\dots,n, j \ne k$$

$$\hat{z}_1^k - \sum_{i=1}^{3} v_{1i}(X_{1i}^k)_\alpha^L \le 0$$

$$\hat{z}_1^j - (\sum_{i=1}^{3} v_{1i}(X_{1i}^j)_\alpha^U) \le 0, j = 1,2,\dots,n, j \ne k \tag{6}$$

$$\hat{z}_2^k - (\hat{z}_1^k + \sum_{i=1}^{3} v_{1i}(X_{2i}^k)_\alpha^L) \le 0$$

$$\hat{z}_2^j - (\hat{z}_1^j + \sum_{i=1}^{3} v_{1i}(X_{2i}^j)_\alpha^U) \le 0, j = 1,2,\dots,n, j \ne k$$

$$u_3(Y_3^k)_\alpha^U - (\hat{z}_2^k + \sum_{i=1}^{3} v_{1i}(X_{3i}^k)_\alpha^L) \le 0$$

$$u_3(Y_3^j)_\alpha^L - (\hat{z}_2^j + \sum_{i=1}^{3} v_{1i}(X_{3i}^j)_\alpha^U) \le 0, j = 1,2,\dots,n, j \ne k$$

$$w_1(Z_1^j)_\alpha^L \le \hat{z}_1^j \le w_1(Z_1^j)_\alpha^U, j = 1,2,\dots,n$$

$$w_2(Z_2^j)_\alpha^L \le \hat{z}_2^j \le w_2(Z_2^j)_\alpha^U, j = 1,2,\dots,n$$

$v_{ti}, u_3, w_1, w_2 \geq \varepsilon,$

$i = 1,2,3; t = 1,2,3$

After calculating the optimal values for v_{ti}^*, u_3^*, w_1^*, w_2^*, $\hat{z}_1^*$, and $\hat{z}_2^*$ Model (6) yields the upper bound α-cut efficiencies of DMU_k for the whole network and for the three processes as follows:

$$(E_k)_\alpha^U = u_3^*(Y_3^k)_\alpha^U \Big/ \sum_{t=1}^{3}\sum_{i=1}^{3} v_{ti}^*(X_{ti}^k)_\alpha^L$$

$$(E_k^1)_\alpha^U = \hat{z}_1^{*k} \Big/ \sum_{i=1}^{3} v_{1i}^*(X_{1i}^k)_\alpha^L$$

$$(E_k^2)_\alpha^U = \hat{z}_2^{*k} \Big/ (\hat{z}_1^{*k} + \sum_{i=1}^{3} v_{2i}^*(X_{2i}^k)_\alpha^L) \tag{7}$$

$$(E_k^3)_\alpha^U = u_3^*(Y_3^k)_\alpha^U \Big/ (\hat{z}_2^{*k} + \sum_{i=1}^{3} v_{3i}^*(X_{3i}^k)_\alpha^L)$$

Formulating the lower bound α-cut efficiencies of the proposed model in Figure 2.1 requires the dual objective function of Model (3) to be transformed to the fuzzy state. Thus, initially the transformed dual version of Model (3) is formulated and subsequently the lower bound α-cut overall efficiency, as well as efficiencies of the three processes (i.e., upstream, organizational, and downstream processes), are presented. The dual format of Model (3) for DMU_k is presented as follows, in line with Kao and Hwang (2008):

$$\tilde{E}_k = \min \theta - \varepsilon((\sum_{t=1}^{3}\sum_{i=1}^{3} s_{ti}^v) + s_1^w + s_2^w + s_3^u) \tag{8}$$

s.t.

$$\theta\tilde{X}_{1i}^{k}-\sum_{j=1}^{n}\alpha_j\tilde{X}_{1i}^{j}-\sum_{j=1}^{n}\beta_j\tilde{X}_{1i}^{j}-s_{1i}^{v}=0, i=1,2,3$$

$$\theta\tilde{X}_{2i}^{k}-\sum_{j=1}^{n}\alpha_j\tilde{X}_{2i}^{j}-\sum_{j=1}^{n}\gamma_j\tilde{X}_{2i}^{j}-s_{2i}^{v}=0, i=1,2,3$$

$$\theta\tilde{X}_{3i}^{k}-\sum_{j=1}^{n}\alpha_j\tilde{X}_{3i}^{j}-\sum_{j=1}^{n}\delta_j\tilde{X}_{3i}^{j}-s_{3i}^{v}=0, i=1,2,3$$

$$\sum_{j=1}^{n}\beta_j\tilde{Z}_{1}^{j}-\sum_{j=1}^{n}\gamma_j\tilde{Z}_{1}^{j}-s_{1}^{w}=0$$

$$\sum_{j=1}^{n}\gamma_j\tilde{Z}_{2}^{j}-\sum_{j=1}^{n}\delta_j\tilde{Z}_{2}^{j}-s_{2}^{w}=0$$

$$\sum_{j=1}^{n}\alpha_j\tilde{Y}_{3}^{j}+\sum_{j=1}^{n}\delta_j\tilde{Y}_{3}^{j}-s_{3}^{u}=\tilde{Y}_{3}^{k}$$

$$\alpha_j,\beta_j,\gamma_j,\delta_j,s_{ti}^{v},s_{1}^{w},s_{2}^{w},s_{3}^{u}\geq 0, j=1,2,\dots,n; i=1,2,3; t=1,2,3$$

Accordingly, the lower bound α-cut overall efficiency of Model (8) will be the following:

$$(E_k)_{\alpha}^{L}=\min\varepsilon((\sum_{t=1}^{3}\sum_{i=1}^{3}s_{ti}^{v})+s_{1}^{w}+s_{2}^{w}+s_{3}^{u})$$

s.t.

$$\theta(X_{1i}^{k})_{\alpha}^{U}-\left[\alpha_k\left(X_{1i}^{k}\right)_{\alpha}^{U}+\sum_{j=1,j\neq k}^{n}\alpha_j\left(X_{1i}^{j}\right)_{\alpha}^{L}\right]-\left[\beta_k\left(X_{1i}^{k}\right)_{\alpha}^{U}+\sum_{j=1,j\neq k}^{n}\beta_j\left(X_{1i}^{j}\right)_{\alpha}^{L}\right]-s_{1i}^{v}=0, i=1,2,3 \tag{9}$$

$$\theta(X_{2i}^{k})_{\alpha}^{U}-\left[\alpha_k\left(X_{2i}^{k}\right)_{\alpha}^{U}+\sum_{j=1,j\neq k}^{n}\alpha_j\left(X_{2i}^{j}\right)_{\alpha}^{L}\right]-\left[\gamma_k\left(X_{2i}^{k}\right)_{\alpha}^{U}+\sum_{j=1,j\neq k}^{n}\gamma_j\left(X_{2i}^{j}\right)_{\alpha}^{L}\right]-s_{2i}^{v}=0, i=1,2,3$$

$$\theta(X_{3i}^{k})_{\alpha}^{U}-\left[\alpha_k\left(X_{3i}^{k}\right)_{\alpha}^{U}+\sum_{j=1,j\neq k}^{n}\alpha_j\left(X_{3i}^{j}\right)_{\alpha}^{L}\right]-\left[\delta_k\left(X_{3i}^{k}\right)_{\alpha}^{U}+\sum_{j=1,j\neq k}^{n}\delta_j\left(X_{3i}^{j}\right)_{\alpha}^{L}\right]-s_{3i}^{v}=0, i=1,2,3$$

$$\sum_{j=1}^{n}\beta_j z_1^j-\sum_{j=1}^{n}\gamma_j z_1^j-s_1^w=0$$

$$\sum_{j=1}^{n}\gamma_j z_2^j-\sum_{j=1}^{n}\delta_j z_2^j-s_2^w=0$$

$$\left[\alpha_k(Y_3^k)_{\alpha}^{L}+\sum_{j=1,j\neq k}^{n}\alpha_j(Y_3^j)_{\alpha}^{U}\right]+\left[\delta_k(Y_3^k)_{\alpha}^{L}+\sum_{j=1,j\neq k}^{n}\delta_j(Y_3^j)_{\alpha}^{U}\right]-s_3^u=(Y_3^k)_{\alpha}^{L}$$

$$(Z_1^j)_{\alpha}^{L}\leq z_1^j\leq\left(Z_1^j\right)_{\alpha}^{U}, j=1,2,\dots,n$$

$$(Z_2^j)_{\alpha}^{L}\leq z_2^j\leq\left(Z_2^j\right)_{\alpha}^{U}, j=1,2,\dots,n$$

$$\alpha_j,\beta_j,\gamma_j,\delta_j,s_{ti}^{v},s_1^w,s_2^w,s_3^u\geq 0, j=1,2,\dots,n; i=1,2,3; t=1,2,3$$

Once the optimal solution is obtained from Model (9), values of $s_{ti}^{*v}, s_1^{*w}, s_2^{*w}, s_3^{*u}$ are assigned to v_{ti}^*, w_1^*, w_2^*, u_3^* respectively and thus the lower bound level of system efficiency and the lower bound efficiency levels of the upstream, organizational, and downstream processes at the α-cut level are calculated as follows:

$$(E_k)_\alpha^L = u_3^*(Y_3^k)_\alpha^L \Big/ \sum_{t=1}^{3}\sum_{i=1}^{3} v_{ti}^*(X_{ti}^k)_\alpha^U$$

$$(E_k^1)_\alpha^L = w_1^* z_1^{*k} \Big/ \sum_{i=1}^{3} v_{1i}^*(X_{1i}^k)_\alpha^U$$

$$(E_k^2)_\alpha^L = w_2^* z_2^{*k} \Big/ (w_1^* z_1^{*k} + \sum_{i=1}^{3} v_{2i}^*(X_{2i}^k)_\alpha^U) \qquad (10)$$

$$(E_k^3)_\alpha^L = u_3^*(Y_3^k)_\alpha^L \Big/ (w_2^* z_2^{*k} + \sum_{i=1}^{3} v_{3i}^*(X_{3i}^k)_\alpha^U)$$

Considering the values for the parameter α, in Models (6) and (9), $\alpha = 0$ and $\alpha = 1$ are particularly important and often used to report the final outcomes of these two models. At $\alpha = 0$ the range of all possible efficiency scores for different values of α is determined. Moreover, at $\alpha = 1$, the most likely efficiency score for the DMUs is obtained. Hence, using the efficiency scores for different values of α and connecting the lower and upper bounds of these efficiency scores, the membership function of the fuzzy resilience levels to supply chain risks is determined. This provides both a system-wide (reflecting the overall supply chain) and a tier-specific evaluation and comparison of resilience/risk ratios across DMUs and among a variety of processes that constitute a supply chain.

In the following section, the suggested fuzzy network DEA model is tested using a survey of 150 middle- and top-level managers representing nine industrial sectors in Iran.

Survey study

Research instrument and data collection

Despite the unique investment opportunities that Iran's main industries offer to foreign investors, Iran's market can still be characterized as conservative and quite restrictive to foreign investors. Lately foreign investment groups, mainly from the European and American region, were offered a chance to participate in further development of main industry sectors in Iran (Hampsheir, 2014; Long, 2015). The ability to assess risk exposures and resilience of the supply chains supporting the core industries in Iran is expected to improve the investment climate by enhancing transparency of these investment opportunities.

All the main industries investigated in this survey study source their materials from either domestic or international suppliers and after processing these materials into final products, they deliver their products to end customers who are mainly located in Iran.

The survey instrument (see Appendix 1) that allowed the participants to evaluate the level of risk exposure in supply chains was adapted from Wagner and Bode (2008). Specifically, in our instrument the risk groupings outlined in the *Background* section (see page 31) were updated. Moreover, the items for supply chain resilience assessment were adopted from '*supply resiliency measures*' introduced by Blackhurst et al. (2011) within three main groups, namely: human capital resources, organizational and inter-organizational capital resources, and physical capital resources. Appendix 1 illustrates the measures used in the survey instrument. Initial testing of the model showed acceptable levels of internal consistency (Cronbach's $\alpha > 0.8$) (Hu & Bentler, 1999) and convergent validity (AVE > 0.7) (Fornell & Larcker, 1981) of the instrument. Additionally, all factor loadings were above 0.45 with no signs of cross loadings. Since the variables have different frequency distributions, we apply the threshold levels suggested by Tabachnick and Fidell (2007) with the following cut-offs: 0.32 (poor), 0.45 (fair), 0.55 (good), 0.63 (very good) or 0.71 (excellent). In view of these cut-off levels, our sample size (n=150) is large enough to generate significant results with a lower factor loading (Hair, Black, Babin, Anderson, & Tatham, 1998). Common method variance is controlled for by maintaining respondents' anonymity and by using well-established fuzzy scales (MacKenzie & Podsakoff, 2012).

To test the model, 150 middle and top managers from nine main industries in Iran (Central Bank of Iran, 2013) were surveyed to rank the resilience to risks in industries they work in, by giving scores to risk and resilience for upstream, organizational and downstream processes of these industries. Specifically the purpose of conducting the survey was to prioritize risk exposures and resilience associated with the model (see

Figure 2.1). Respondents took part in an educational program, conducted by one of the major universities in Iran, to enhance their skills in the fields of business administration and operations management. The program was delivered online for six months under the supervision of this university, the copies of the survey were initially distributed to the participants via e-mail. After two rounds of follow-ups, a total response rate of 84% was obtained. The high value of response rate was primarily due to the fact that the survey was presented during the course of the educational program, although it was not compulsory. The average work experience of the respondents was six and a half years with the maximum of fifteen years and minimum of three years of managerial experience. The demographics of the respondents are presented in Table 2.3.

Table 2.3 Descriptive statistics of the survey sample (n=150)

Industry	Number	Percentage of total	Cumulative Percentage
Gender			
Female	30	24	24
Male	96	76	100
Total	126	100	
Age			
< 30	10	8	8
30–60	83	66	74
>60	33	26	100
Total	126	100	
Industry			
Automobile	10	8	8
Construction	14	11	19
Food processing	16	13	32
IT and Telecommunications	12	9	41
Machinery	14	11	52
Oil and Petroleum	19	16	68
Pharmaceutical and Medical	15	12	80
Steel	12	9	89
Textile	14	11	100
Total	126	100	

Results

Respondents were asked to evaluate the inputs, outputs, and intermediary inputs/outputs illustrated in Figure 2.1 and outlined in Appendix 1, using linguistic variables (from 'Extremely low' to 'Extremely high'). The respondents evaluated all risk and resilience items for the supply chains, associated with the industries they were working in. The number of respondents representing each supply chain is enumerated in Table 2.3. To test the core assumptions of the model, while risk items were different for upstream, organizational or downstream processes, resilience items for those processes remained the same. These linguistic variables were in turn interpreted as TFNs (see earlier section entitled "*Applying fuzzy sets and* α*-cut approach to the proposed network DEA model*", page 44) within the range of [1–9]. The corresponding TFNs for all the linguistic variables used in the survey were: 'Extremely low' (1, 1, 3), 'Low' (1, 3, 5), 'Fair' (3, 5, 7), 'High' (5, 7, 9), and 'Extremely high' (7, 9, 9). For instance, if a respondent evaluated a risk item (e.g., dependence of manufacturer on a single source of supply) as 'High', the corresponding TFN was (5, 7, 9). Following Dubois and Prade (1978), for each industry the average fuzzy ratings of risk and resilience items was extracted and aggregated to obtain the final ratings characterizing the main risk groups and supply chain resilience. The average values for inputs, outputs, and intermediary inputs/outputs of the model in Figure 2.1 are presented in Table 2.4.

Table 2.4 Average triangular fuzzy numbers extracted for the inputs, output, and intermediary inputs/outputs of the three-tier supply chain

Industry	X_{11}	X_{12}	X_{13}	X_{21}	X_{22}	X_{23}	X_{31}	X_{32}	X_{33}	Z_1	Z_2	Y_3
Automobile	(5,7,8.6)	(2.6,4.2,6.2)	(1.8,2.2,4.2)	(6.2,8.2,9)	(2.2,3.4,6.2)	(4.2,6.2,8.2)	(1.4,1.8,3.8)	(1.8,3.4,5.4)	(4.6,6.6,8.2)	(4.2,6.2,8.2)	(1,1.8,3.8)	(1.8,3.4,5.4)
Construction	(3.4,5.4,7.4)	(1.8,3.4,5.4)	(1.4,3.4,5.4)	(5,6.6,9)	(1.4,3,5)	(2.2,4.2,6.2)	(3,5,7)	(1.4,2.6,4.6)	(3.4,5.4,7.4)	(2.6,3.8,5.8)	(1,1.4,3.4)	(2.6,4.6,6.6)
Food Processing	(2.6,4.2,6.2)	(2.6,4.6,6.6)	(1.4,2.6,4.6)	(4.6,6.6,8.2)	(2.2,3.8,5.8)	(1.8,3.8,5.8)	(1.2,2.2,4.2)	(2.2,4.2,6.2)	(3.8,5.8,7.8)	(2.2,4.2,6.2)	(4.2,6.2,8.2)	(5,7,8.6)
IT and Telecommunications	(3.4,5.4,7.4)	(1,2.2.,4.2)	(1.8,3.8,5.8)	(3.4,5.4,7.4)	(1.4,2.6,4.6)	(3.8,5.8,7.8)	(1,1.4,3.4)	(1.8,2.2,4.2)	(1,2.2.,4.2)	(1.8,3.8,5.8)	(4.2,6.2,8.2)	(3.8,5.8,7.8)
Machinery	(4.2,6.2,8.2)	(1.8,3.8,5.8)	(1,2.2,4.2)	(3.8,5.8,7.8)	(1.4,3.4,.5.4)	(1.4,3,5)	(1.4,2.6,4.6)	(1.4,3.4,5.4)	(4.2,6.2,8.2)	(4.6,6.6,8.2)	(1.8,3.8,5.8)	(1.4,3,5)
Oil and Petroleum	(1.8,3.4,5.4)	(1,2.2,4.2)	(4.2,6.2,7.8)	(2.6,4.2,6.2)	(1,1.8,3.8)	(5.4,7.4,8.6)	(1,1.4,3.4)	(1.4,2.6,4.6)	(1.8,3.4,5.4)	(1.4,2.2,4.2)	(1,1.4,3.4)	(5.4,7.4,8.6)
Pharmaceutical and Medical	(6.2,7.4,9)	(4.2,6.2,7.8)	(3.8,5.8,7.8)	(1.4,3,5)	(1.4,3,5)	(6.2,7.4,9)	(3,4.2,6.2)	(1,2.6,4.6)	(6.2,7.4,9)	(3.8,5.8,7.8)	(1.8,3.8,5.8)	(4.6,6.2,8.2)
Steel	(5.4,7.4,8.6)	(3.8,5.8,7.8)	(1.4,1.8,3.8)	(4.6,6.6,7.8)	(3,5,7)	(5.4,7.4,8.6)	(3.8,5.4,7.4)	(1.8,3.8,5.8)	(3.8,5.8,7.8)	(4.2,6.2,7.4)	(2.2.,4.2,6.2)	(2.2.,4.2,6.2)
Textile	(2.2,4.2,6.2)	(1.4,1.8,3.8)	(1.8,3.8,5.8)	(5,7,8.6)	(1.8,2.6,4.6)	(2.2,4.2,6.2)	(1.8,3,5)	(1.4,2.2,4.2)	(1.4,1.8,3.8)	(1.8,3.8,5.8)	(3,5,7)	(2.2,4.2,6.2)

MATLAB 2014b was used to code the model and generate the comparative diagrams of membership functions. As discussed earlier, the cut-off values of $\alpha = 0$ and $\alpha = 1$ are often used to determine the range and the most likely value of the efficiency score, respectively. Considering this, in Table 2.5 the upper bound (UB) and lower bound (LB) efficiency scores of the nine supply chains for $\alpha = 0$ and $\alpha = 1$ are individually presented for three tiers, as per the model outlined in Figure 2.1.

In line with the results reported in Figure 2.1, the supply chain associated with the Food Processing industry received the highest overall resilience to risk score, referred to as 'efficiency score', $(\tilde{E}_k = 0.70)$ at $\alpha = 1$ followed by IT and Telecommunications $(\tilde{E}_k = 0.68)$ and Oil and Petroleum $(\tilde{E}_k = 0.60)$ supply chains. These results indicate a comparatively high degree of resilience to risk in the supply chains characterizing these industries. Tier-specific comparisons of the results provide further insights into the efficiency scores of the individual supply chain tiers. As it is indicated in Table 2.5, these scores are not necessarily aligned with the rankings of the overall supply chains efficiency scores.

Table 2.5 α-cuts of the fuzzy efficiency scores in the three-tier supply chain

Industry	Overal l Rank	$\alpha = 0$				$\alpha = 1$			
		Overall (LB, UB)	Tier 1 (LB, UB)	Tier 2 (LB, UB)	Tier 3 (LB, UB)	Overall (LB, UB)	Tier 1 (LB, UB)	Tier 2 (LB, UB)	Tier 3 (LB, UB)
Automobile	7	(0.12, 1.00)	(0.16, 0.48)	(0.16, 0.50)	(0.15, 0.49)	(0.31, 0.31)	(0.28, 0.28)	(0.29, 0.289)	(0.36, 0.36)
Construction	5	(0.14,1.00)	(0.27, 0.94)	(0.04, 0.22)	(0.38, 0.68)	(0.51, 0.51)	(0.74, 0.74)	(0.156, 0.16)	(0.62, 0.62)
Food Processing	1	(0.27,1.00)	(0.68, 0.97)	(0.52, 0.78)	(0.14, 0.87)	(0.70, 0.70)	(0.87, 0.87)	(0.63, 0.63)	(0.60, 0.60)
IT and Telecommunications	2	(0.32,1.00)	(0.10, 0.46)	(0.52, 0.88)	(0.73, 1.00)	(0.68, 0.68)	(0.42, 0.42)	(0.70, 0.70)	(0.93, 0.93)
Machinery	8	(0.07,1.00)	(0.01, 0.36)	(0.02, 0.36)	(0.04, 0.36)	(0.28, 0.28)	(0.28, 0.28)	(0.25, 0.25)	(0.31, 0.31)
Oil and Petroleum	3	(0.49,1.00)	(0.19, 0.50)	(0.23, 0.53)	(0.80, 1.00)	(0.60, 0.60)	(0.33, 0.33)	(0.48, 0.48)	(1.00, 1.00)
Pharmaceutical and Medical	4	(0.29,1.00)	(0.03, 0.18)	(0.56, 0.87)	(0.66, 1.00)	(0.58, 0.58)	(0.11, 0.11)	(0.78, 0.78)	(0.84, 0.84)
Steel	9	(0.08,1.00)	(0.01, 0.23)	(0.02, 0.23)	(0.16, 0.49)	(0.20, 0.20)	(0.10, 0.10)	(0.12, 0.12)	(0.39, 0.39)
Textile	6	(0.15,1.00)	(0.15, 0.56)	(0.09, 0.28)	(0.48, 1.00)	(0.39, 0.39)	(0.35, 0.35)	(0.15, 0.15)	(0.67, 0.67)

For instance, while Pharmaceutical and Medical supply chain is ranked fourth, it shows better resilience to supply chain risks in organizational processes $(\tilde{E}_k^2 = 0.78)$ than all the other three top supply chains (see Figure 2.2 for comparisons of membership functions). In another example, the supply chain associated with the Construction industry, ranked in the fifth place, demonstrated the second best efficiency score in upstream processes $(\tilde{E}_k^1 = 0.74)$. There are noticeable differences in the efficiency scores of the three tiers for the top three supply chains ranked in Table 2.5. IT and Telecommunications supply chain shows higher resilience to risk exposures than Food Processing supply chain in both organizational processes and downstream processes. Also, Oil and Petroleum supply chain is ranked first as the most resilient to supply chain risks in downstream processes. Figures 2.3–2.5 compare efficiency scores in three tiers for the top three supply chains in Table 2.5 (i.e., Food Processing, IT and Telecommunications, and Oil and Petroleum).

Figure 2.2 Efficiency score comparisons for Pharmaceutical and Medical, Food Processing, IT and Telecommunications, and Oil and Petroleum supply chains in organizational processes

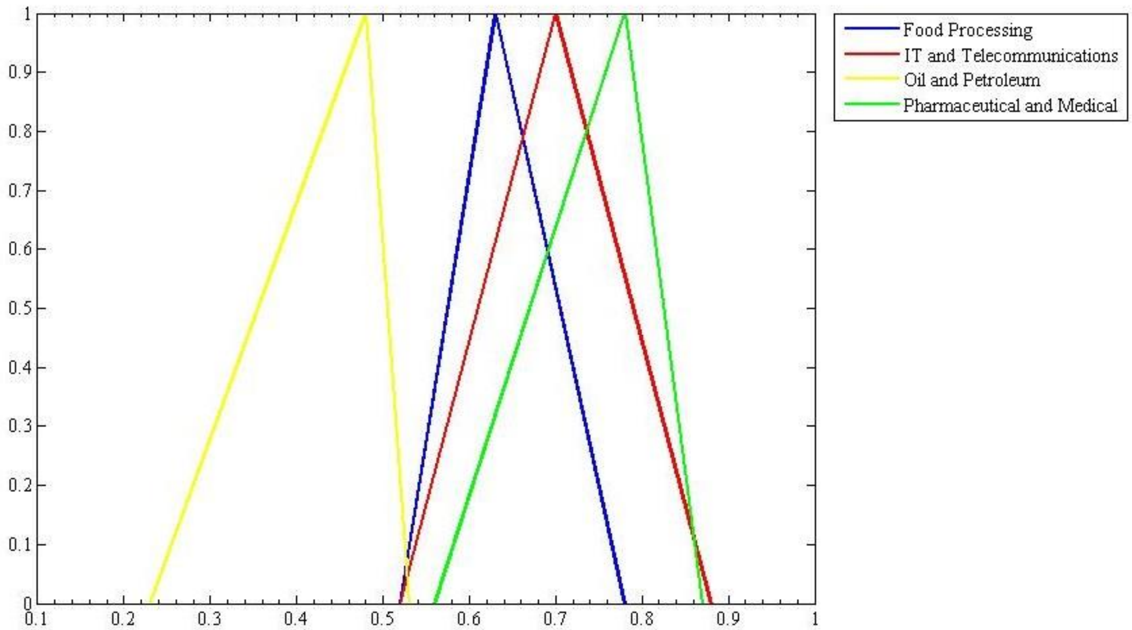


Figure 2.3 Efficiency score comparisons for Food Processing, IT and Telecommunications, and Oil and Petroleum supply chains in upstream processes

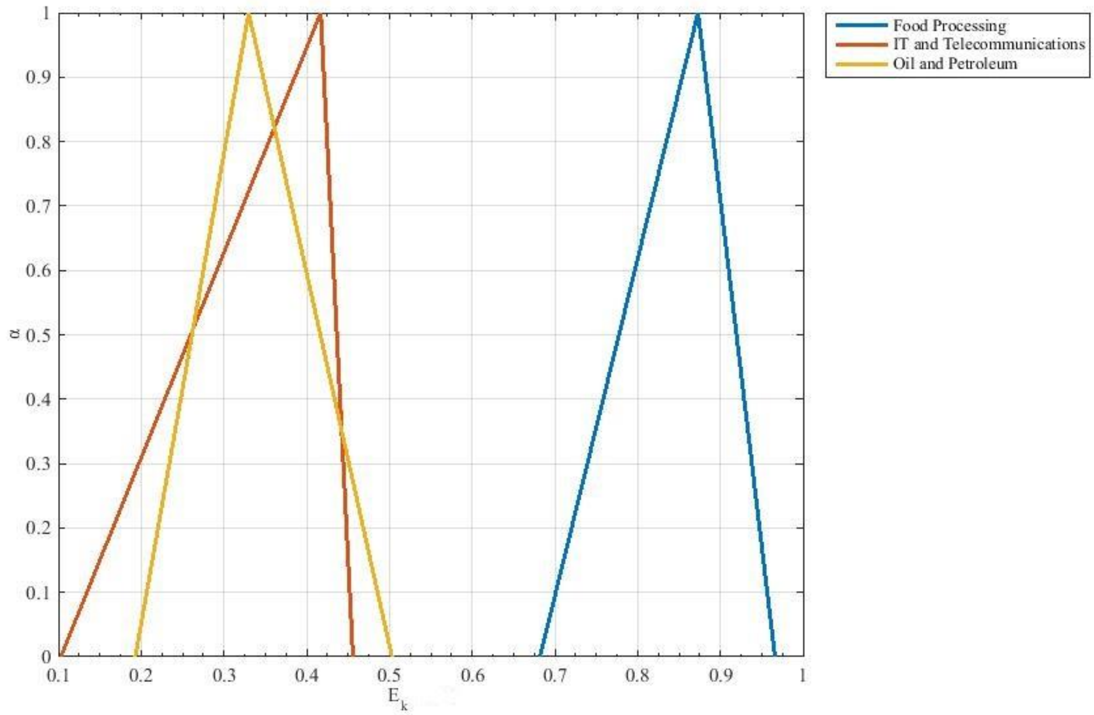


Figure 2.4 Efficiency score comparisons for Food Processing, IT and Telecommunications, and Oil and Petroleum supply chains in organizational processes

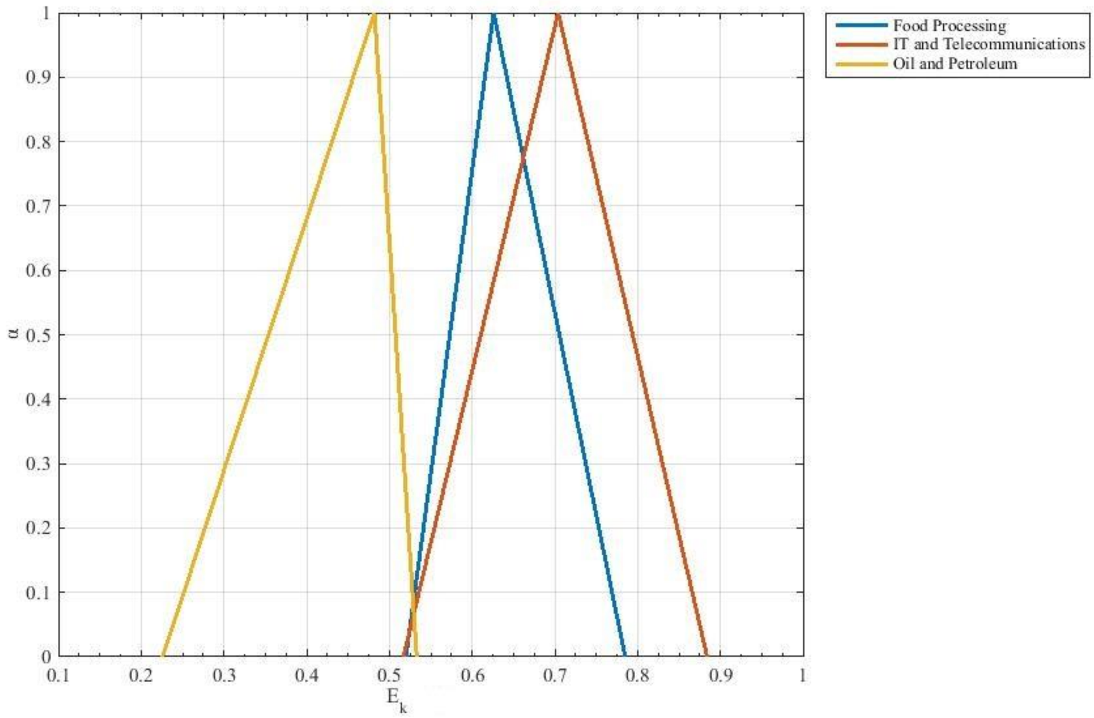
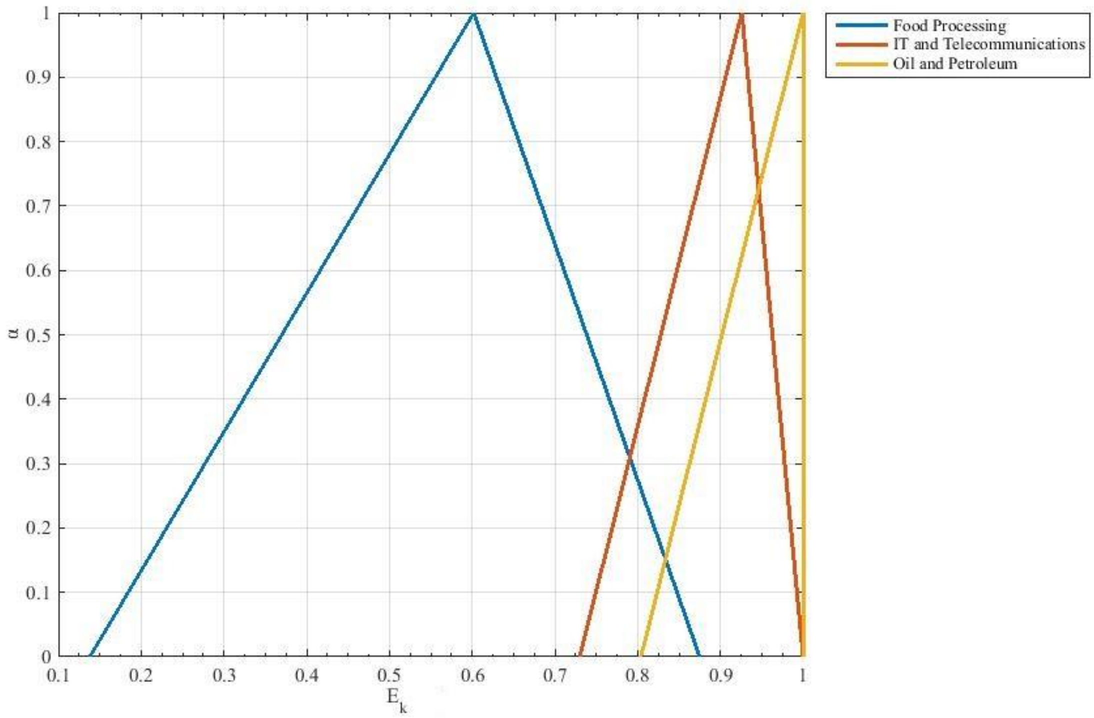


Figure 2.5 Efficiency score comparisons for Food Processing, IT and Telecommunications, and Oil and Petroleum supply chains in downstream processes



Figures 2.3–2.5 also reveal the differences in efficiency scores across tiers of the top three supply chains. Food Processing membership function (illustrated in blue), for instance, is more efficient in upstream processes and lags behind both IT and Telecommunications and Oil and Petroleum supply chains in downstream processes. Food Processing and IT and Telecommunications supply chains, on the other hand, show a close proximity in efficiency levels of their organizational processes.

An inefficiency breakdown of the aforementioned top three supply chains is presented in Table 2.6. Such breakdown helps identifying variables to be improved for both sets of inputs and outputs by proposing a percentage change in these variables against the benchmark frontier. Bold numbers show the maximum percentage change for each variable across the three supply chains.

Table 2.6 Forecast changes in input and output variables against the benchmark frontier (% change)

Upstream processes				
	Excess upstream risks[a]	Excess external risks	Excess network risks	Shortage supplier resilience[b]
Food Processing	–8.36	**–3.20**	0.00	0.00
IT and Telecommunications	**–11.10**[c]	0.00	–6.73	5.96
Oil and Petroleum	0.00	0.00	**–13.68**	**6.83**
Organizational processes				
	Excess organizational risks	Excess external risks	Excess network risks	Shortage manufacturer resilience
Food Processing	**–7.74**	**–2.21**	–1.41	0.00
IT and Telecommunications	–6.15	–1.93	–3.44	0.00
Oil and Petroleum	–3.70	0.00	**–10.63**	**4.27**
Downstream processes				
	Excess downstream risks	Excess external risks	Excess network risks	Shortage distributor resilience
Food Processing	0.00	**–4.66**	**–5.38**	1.00
IT and Telecommunications	–1.38	0.00	0.00	**5.97**
Oil and Petroleum	–1.37	0.00	–1.24	1.25

[a] *Excess indicates percentage decrease in inputs against efficient frontier*

[b] *Shortage indicates percentage increase in outputs against efficient frontier*

[c] *Bold numbers illustrate the largest changes projected for per variable*

According to Table 2.6, upstream risks seem to represent the highest threat to the IT and Telecommunications industry by affecting its upstream processes (excess –11.10 %). The same pattern could be observed for: the supply chain associated with Food Processing industry and its exposure to external risks (excess –3.20 %), and also for the Oil and Petroleum supply chain exposed to high network risks (i.e., risks in supplier-manufacturer relations, excess –13.68 %). The resilience shortage amounts reported in Table 2.6 for upstream processes indicate that Oil and Petroleum industries (shortage 6.83%) are the least resilient among the top three supply chains in their upstream processes. Tracing this lack of resilience to the risk exposures, this implies that Oil and Petroleum supply chain should closely monitor network risks and the relationship between suppliers and manufacturers. Moreover, resilience of upstream processes could be increased in Oil and Petroleum industries by investing additional resources in such supply chain resilience factors as human capital resources, organizational and inter-organizational capital resources, and physical capital resources, as proposed by Blackhurst et al. (2011). The efficiency scores of the IT and Telecommunications supply chain tiers indicate that the effort associated with resilience improvement should include both upstream and downstream processes. Moreover, comparisons against the benchmark frontier show that the primary focus of IT and Telecommunications should be on mitigating risks associated with their upstream and organizational processes.

The results presented in tables 2.5 and 2.6 and figures 2.2–2.5 support the argument on the merits of adopting both a system-wide and a tier-specific approach for the assessment of resilience to risks in supply chains. The outcomes show that while a supply chain system could be construed by the managers as resilient to risk exposures, its individual tiers may still be susceptible to risks, which need to be property accounted and incorporated into the resilience model. If not properly and timely mitigated, these risks may propagate further throughout the supply chain affecting the overall supply chain resilience and potentially resulting in supply chain disruptions. Thus, even though an overall supply chain efficiency score is indicative of the ability of a supply chain system to efficiently react to risks maintaining the continuity of core processes within the system, the resilience levels at different tiers of a given supply chain may vary substantially.

Based on the presented results, in the next section we discuss how practitioners and supply chain decision makers could leverage the results obtained from the suggested fuzzy network DEA model to decide about investing in practices that help improving supply chain resilience, mitigate supply chain risks, or both.

Discussion and implications

Supply chain resilience is a necessary condition to assure survival and prosperity of supply chains exposed to a wide and continuously changing spectrum of risks, both at global and national levels. Proficiency regarding where to invest in supply chain resilience can lead to supply chains that respond quicker and recover faster from costly disruptions (Jüttner & Maklan, 2011). However, often it is quite difficult for firms to identify where exactly the major/primary sources of risk exposure originate from; thereby, making the risk identification process increasingly taxing. Building on general systems theory as well as the emerging theory of the supply chain proposed by Carter et al. (2015), it has been demonstrated in this study that in order to gain a better insight into resilience to supply chain risks, resilience should be assessed both at the level of individual tiers and supply chain system as a whole. The dual perspective on supply chain resilience assessment was therefore suggested with the view to minimize the adverse effects of the realised risks upon individual tiers and the overall supply chain.

To address the aforementioned aim, a fuzzy network DEA model was proposed, allowing to extend the functionality of the previous models and specifically to analyse and compare supply chain resilience to risks at two levels: (i) for individual tiers of a supply chain; and (ii) for the overall supply chain conceptualized as a complex system. A survey of 150 managers was subsequently conducted to test the proposed model in the context of nine main industrial supply chains in Iran. Based on the survey study results, the capabilities of the proposed fuzzy network DEA model in providing insights into both the system-wide and tier-specific resilience in supply chains have been demonstrated. The empirical results of the survey allowed for the provision of a number of practical and generalizable recommendations to the managers working in the nine surveyed industries in Iran. This however does not constrain the applicability of our model to a specific industry/supply chain, since the model is flexible and could be applied in different contexts.

The results of the empirical analysis show that the resilience level associated with the overall supply chain is not necessarily indicative of the resilience of its individual tiers. Similarly, high efficiency scores of a number of tiers forming a supply chain is shown to have only a limited effect on the overall efficiency score of the resulting supply chain. This supports the view voiced in the studies investigating the characteristics of emergence and complexity as fundamental properties accounting for non-linearity in the behaviour of the supply chains (Carter et al., 2015; Choi & Krause, 2006). These characteristics have also been reported as detrimental for the visibility of individual supply chain members (Carter et al., 2015; World Economic Forum, 2013), including the ability to visualize risks of the supply chain members (Neiger et al., 2009).

The risks that threaten the continuity of supply chains are the low probability - high impact events. The lack of historical data around those rare occurrences commonly leading to the disruptions of the core value adding processes in supply chains generally leave the practitioners the following plausible options for tapping into uncertainty: designing and running simulation models based on the synthetic data, extrapolate the effects of the potential disruptive events based on expert knowledge of process owners and other parties who have extensive situational knowledge about the processes of interest, or the combination of these two approaches. This study provides an analytical model, which allows the practitioners to use expert knowledge in order to conduct a dual resilience assessment at the level of the overall supply chain and its individual tiers. It should be noted that the vulnerability assessment of the overall supply chain represents an aggregate measure of the overall supply chain susceptibility to risk providing very limited diagnostic capability in order to identify the core threats to the continuity of the business processes within the supply chain. On the other hand, separate assessments of the resilience scores for the individual tiers of the supply chain are not necessarily indicative of its overall resilience level, as in line with the complex adaptive systems perspective, adopted in our study, the overall system characteristics do not represent the product of summing up the characteristics of its individual components. Therefore, our study provides a measurable approach to identify threats to the continuity of supply chain value-adding activities by suggesting an analytical approach that enables to conduct the assessment of supply chain resilience at both system-based and tier-specific levels.

Our study provides descriptive insights for practitioners by creating a proposed model for supply chain resilience assessment to risk exposures and then subsequently comparing the efficiency scores of nine different industries. The comparison allows managers to reflect upon the typical environmental conditions within their industry (see figures 2.2–2.5), distinguishing where any differences may exist, and thereby facilitating strategy formulation processes. Overall, the managerial implications resonate with the research implications, in that the system wide and tier specific approach towards understanding resilience to supply chain risks facilitates deeper insights than previously possible This approach provides the opportunity for supply chain decision makers to prioritize risk sources to be mitigated/managed (whenever possible) and resilience enhancement practices to invest in.

In summary, our research findings confirm the necessity of adopting both the system-wide and tier-specific approach by analysts and decision makers when assessing supply chain resilience. From the top-down perspective, such approach should consider the structure of the supply chain and potential threats, both internal and external, associated with its core value drivers and deliverables. The bottom-up approach would consider the threats associated with inflows, outflows, resources and key deliverables associated with supply chain partners and thereby directly contributing to the overall level of the supply chain resilience. Hence, a realistic measure of the overall supply chain resilience can only be achieved given coordinated effort of all parties in terms of the assessment of risks associated to the overall supply chain or one of its components. Performing such a composite assessment of supply chain resilience at both the systems and tier levels allows to identify any substantial differences in efficiency scores across distinct tiers of supply chains. Integrated as part of risk response and mitigation process, such information ensures timely identification and mitigation of major sources of risk in the supply chains.

Limitations and future research

This study comes with some caveats. First, the results would have been more accurate if both main risk groups and their measures were formulated in the model. This would have resulted in a hierarchical model formulated in line with Kao's (2015) hierarchical network DEA modelling approach or the two-level DEA approach of Meng et al. (2008). Such model enhancement could also provide a more in-depth view into the specific sources of risk that have the most adverse effect on supply chain resilience.

In this study, we modelled risk and resilience in a simplest form of a three-tier supply chain with no inclusion of indirect effects. However, network DEA is capable of modelling parallel networks as well as series more than three tiers in a network (for more information see, Kao, 2014b). For instance, if supplier resilience affects both manufacturer and distributor, this could be modelled using a parallel structure or when there are multiple suppliers or distributors working in tandem, depending on the order of the processes, both parallel and series structures could be applied to model the supply network.

Our model does not explicitly capture the effects of reverse causality and feedbacks between the actors (or major processes) within the system, which should be clearly regarded as a limitation of our approach. Our model does not capture either such product of non-linear dynamic behaviour as time delays. The task of addressing these properties is beyond the scope of this study and makes part of the possible future research directions. We believe that this task would be most appropriately addressed by using the reach toolset of system dynamics modelling, or a hybrid simulation approach which would draw upon – depending on the goal of the follow up study – the integrated use of system dynamics and agent based modelling, system dynamics and discrete event simulation, or even on the integration of these three simulation modelling approaches. Such aggregated use of multiple simulation modelling approaches is supported by such simulation engines as AnyLogic (among others) and would certainly represent a very interesting research avenue for building and testing supply chain resilience assessment models."

In addition, the precision of resilience assessment in supply chains could be improved by incorporating *supply chain orientation* and *firm's resource reconfiguration capabilities*, in line with another holistic supply chain resilience assessment framework recently proposed by Ambulkar et al. (2015). Finally, the suggested fuzzy network DEA model for supply chain resilience assessment was validated in a country-specific setting comprising nine major industry sectors of Iran. To increase external validity of the model, further studies might test the model in the context of other countries and regions to see whether the reported discrepancy between the resulting system-wide and tier-specific resilience assessment scores are observed in other settings.

Future studies may further explore the applied aspects of supply chain performance and resilience assessment. They may adopt different methodological approaches to improve the assessment of supply chain resilience at various levels – moving from a system-wide perspective of the supply chain toward an organization-specific perspective of individual supply chain tiers. For instance, structural models could be developed that link supply chain risk variables to supply chain resilience variable(s). These models could be empirically tested in different industrial and services contexts to determine the severity of impact for each risk group on supply chain resilience. Furthermore, the results of this study demonstrate that risk assessment throughout supply chain tiers may not be analogous across industries, highlighting the need to further explore the boundary conditions of the proposed model.

2.4. Paper 3: Operational risks and supply chain performance assessment: Case of outsourcing[4]

Outsourcing performance quality assessment using data envelopment analytics

Abstract

The growth of vendor procurement and supply chain management simultaneously emerged as organizational outsourcing practices increased. Outsourcing, as an important strategic organizational practice, needs to be carefully examined from an organizational performance perspective to ensure satisfactory quality of services and goods from supply chains. This article provides a model for performance assessment of an outsourcer's processes in a supply chain comprised of several internal and external entities. Internal entities are entities in a supply chain that the outsourcer can manage and control. External entities are entities whose processes are not within the management sphere and control of the outsourcer, yet affect an outsourcer's performance. A slacks-based measure is incorporated into a hybrid network data envelopment analysis model to evaluate the outsourcer performance incorporating both entity types. A case study of a service supply chain in the banking industry comprised of a commercial bank, its sub-processes, and an external investment bank is used as an illustrative application of the model. Insights are presented and future research directions are identified.

Keywords: Outsourcing; Performance Measurement; Quality; Data Envelopment Analysis; Slacks-Based Measure; Hybrid Network; Supply Chain Management.

Introduction

Strategic focus, core competency development, technological advancements, and ever-increasing competitiveness in markets have motivated more companies to opt for

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[4] Pournader, M., Kach, A. P., Fahimnia, B., & Sarkis, J. (2016). Outsourcing Performance Quality Assessment Using Data Envelopment Analytics. *International Journal of Production Economics (Rank A*)*, Jul. 2016. (In press).

outsourcing solutions (Steven, Dong, & Corsi, 2014; Tate, Ellram, Bals, & Hartmann, 2009). Outsourcing can occur anywhere throughout the supply chain, including upstream, downstream, and organizational processes especially where the inflow or outflow of material, information, or finances cannot be effectively and efficiently developed (Holcomb & Hitt, 2007; Wuyts, Rindfleisch, & Citrin, 2015).

Despite the underlying operational and financial benefits that may accrue from the flexibility to outsource, numerous issues do arise. For example, as the scale and distance of outsourcing increases so do the costs associated with control and coordination amongst supply chain members (Ellram, Tate, & Billington, 2007; Hallikas et al., 2004b; Handley & Benton Jr, 2013). Other related issues may include opportunistic behaviour of suppliers and inadequate relationship management between outsourcer and supplier (Kenneth H Wathne & Heide, 2000), poor quality of services/goods provided by suppliers (Franca, Jones, Richards, & Carlson, 2010), poor inventory management (Lee, 1997), and operational and logistics disruptions in supply chain tiers (Wagner & Bode, 2008). Hence, increasing awareness and information about the quality and performance issues helps the outsourcer to better identify inefficiencies within its internal and external supply chain processes. There is a need for more investigations to extend the scope of quality assessment in outsourcing to consider supply chain operations as a whole (Handley & Gray, 2013; Steven et al., 2014).

From an organizational performance perspective, outsourcing can result in information loss, information asymmetry, and lack of knowledge of the outsourced processes (Ellram, Tate, & Billington, 2008; Handley & Gray, 2013), which in turn inhibits the outsourcer from gaining proper insight into the quality issues that might arise from both outsourced and insourced supply chain processes. Usually the analytical models for performance assessment in supply chains consider a centralized supply chain system in which all the information is available to the outsourcer (Chang, Tone, & Wei, 2014). In this article data envelopment analysis (DEA) is adopted to facilitate a comparative quality assessment in outsourcing activities built upon organizational performance and practiced in supply chains while considering the control and visibility limitations of outsourcing. DEA is a multiple-input multiple-output performance evaluation tool that has been extensively applied to supply chain management and evaluation problems (Liang, Yang, Cook, & Zhu, 2006a; Xu, Li, & Wu, 2009). One particular form of DEA, network DEA, is a valuable tool for evaluating multi-tier supply chains (Chen & Yan, 2011). Using a hybrid network DEA model developed by Chang et al. (2014) and a slacks-based measure (SBM) approach (Kao, 2014a; Tone & Tsutsui, 2009), this study introduces a performance assessment methodology evaluating outsourced processes in both internal and external supply chain entities.

The contributions of this study are threefold. (1) This article accounts for relevant information from internal and external entities in a supply chain to accurately assess the performance of an outsourcer. (2) The combined SBM approach and hybrid network DEA model proposed for the first time in this study provides a customized performance assessment tool with a high discrimination power that could facilitate identifying sources of inefficiencies in supply chain processes. (3) This study is among the few conducted that encourage the application of network DEA instead of traditional DEA models due to their accuracy and extended applications in supply chain performance measurement.

The article is organized as follows. In the next section, *Literature Background*, we review the literature of outsourcing and quality in supply chains. We also review the applications of DEA, specifically network DEA and the SBM approach, and their applicability to the context of our research. The subsequent section includes developing the analytical model to compare performance in multiple supply chains that practice outsourcing. We then test our proposed model in a case study, a service supply chain of Iranian commercial bank. Finally, we discuss our findings and draw conclusions.

Literature background

Quality concerns in outsourcing practices of supply chains

Since the late 20th century, outsourcing has become an inextricable part of strategic decisions made by global companies to achieve cost reduction, increased productivity, and enhanced quality (Chen, Liang, & Yang, 2015; Gray, Tomlin, & Roth, 2009). Outsourcing practices range from activities associated with managing information technology and business processes to the actual manufacturing and production of goods or services (Gunasekaran, Irani, Choy, Filippi, & Papadopoulos, 2015; Steven et al., 2014). Moreover, outsourcing decisions vary substantially from out-tasking to full-outsourcing (for more information see, Sanders, Locke, Moore, & Autry, 2007), which makes outsourcing a flexible and preferred choice by both manufacturing and service companies for diverse outsourcing strategies.

However, there are downsides to outsourcing practices adopted by companies amongst which quality concerns of downstream and/or upstream supply chain members and lack of control over these members play a critical role (Kaya & Özer, 2009; Xiao, Xia, & Zhang, 2014). As supply chains extend their outsourcing practices, the low visibility of their suppliers' or distributors' processes could lead to quality issues such as substandard quality of material, non-conformity to manufacturing specifications, and poor goods maintenance of in logistics operations, for example (Tse & Tan, 2012; Yang et al., 2009).

Despite the abundance of research focusing on quality management issues within an individual firm or entity (Sousa & Voss, 2002), literature on quality issues of outsourcing in the context of supply chains is scarce (Kouvelis, Chambers, & Wang, 2006; Robinson & Malhotra, 2005; Steven et al., 2014). Recent investigations into supply chain quality management has focused on managing the quality of contract manufacturers and the impact of facility audits and contractual penalties (Handley & Gray, 2013). Several outsourcing decisions such as make-or-buy decisions, offshoring, offshore product relocation and supply base consolidation on quality of product recalls have been investigated across several industries (Steven et al., 2014). The applications of various analytical models, such as game theory, for strategic outsourcing decisions of competing buyers for quality improvement and quality competition, have also been investigated (Bae, Yoo, & Sarkis, 2009; Xiao et al., 2014).

Managing organizational performance can significantly enhance quality of services and products delivered by supply chains. The truism that you cannot manage what you cannot measure is especially pertinent when it comes to performance measurement and quality (Adams, Sarkis, & Liles, 1995). This statement is valid and even more important across the supply chain due to the complex nature of interrelations between and amongst supply chain members (Bai & Sarkis, 2012). Given that quality of goods and services in supply chains is dependent on effective performance measurement, in this study we specifically focus on performance criteria in service outsourcing. The case study for testing the applicability of the proposed model sets the foundation for performance effectiveness and quality services in a banking setting.

Assessing the performance of outsourcers in general has been hitherto subject to various studies, proposing different performance metrics and analytical frameworks to this end (e.g., Bustinza, Arias-Aranda, & Gutierrez-Gutierrez, 2010; Feng, Fan, & Li, 2011; Kenyon, Meixell, & Westfall, 2016). Outsourcing has also been viewed through the prism of various theoretical backgrounds (e.g., Ellram et al., 2008; McIvor, 2009). Based on the recent exemplary review of the literature by Gunasekaran et al. (2015), the performance metrics in outsourcing could be classified according to the outsourcing phase (pre-/during-/post-outsourcing stage) and the type of the performance metrics, which in turn could be monetary or non-monetary. Reviewing the performance measurement models in outsourcing, Gunasekaran et al. (2015) enumerate a wide range of tools and techniques from game-theoretic related models to multi-criteria decision analysis and decision support system tools. As part of their suggestions for future research, Gunasekaran et al. (2015) invite researchers to develop "suitable mathematical [and simulation] models" with the purpose of analysing outsourcing decisions. They call for models that could prioritize the exiting outsourcing criteria for both outsourcers and the outsourced companies. This requires an analytical model that is capable of measuring outsourcing performance at the level of supply chain tiers and the supply chain system as a whole.

By shifting the attention from manufacturing outsourcing, services outsourcing has been growing substantially for the past two decades (Caniato, Elia, Luzzini, Piscitello, & Ronchi, 2015; Perdikaki, Peng, & Heim, 2015). However, there have been controversies regarding the efficiency of outsourcing in service supply chains, increasing sensitivity towards applying solutions for improving the quality of their outsourcing practices (Ellram et al., 2007). The main issue revolving around services outsourcing and offshoring include loss of knowledge and understanding of the outsourced operations, hence limiting the ability of the outsourcer to evaluate upstream or downstream supply chain members and their quality (Ellram et al., 2008). There have been calls for more investigations on services outsourcing (Roth & Menor, 2003). Studies addressing certain aspects to this issue do exist (e.g., Bardhan & Kroll, 2003; Caniato et al., 2015; Farrell, Laboissière, & Rosenfeld, 2006; Feng et al., 2011; Lewin & Peeters, 2006). But, the literature still lacks a model and methodology explicating the dynamics of outsourcing and especially services outsourcing for measuring performance in supply chains

(Gunasekaran et al., 2015). Helping to fill this gap, we address some of these performance and quality concerns in the services outsourcing supply chain environment.

Analytical model

Network DEA combined with the SBM approach

Since the introduction of data envelopment analysis (DEA) (Charnes et al., 1978) numerous studies have been conducted based on DEA and its combinations with various mathematical and/or statistical models to measure relative efficiency of decision making units (DMUs) (see Cook & Seiford, 2009; Liu, Lu, Lu, & Lin, 2013a; Liu et al., 2013b). DEA is a multiple input/multiple output analytical model that is capable of comparing several entities/decision making units (DMUs) (i.e., supply chains in this context) based on their performance according to the values of the inputs/outputs. DEA uses a Pareto frontier marked by one or several DMU(s) to rank other DMUs accordingly. Using the DEA modelling, a linear programming model per each DMU is solved according to the values for inputs and outputs. This process will assign weights to each linear aggregation and the DMUs that constitute the Pareto frontier are chosen based on the assumption that, given the same weights, no other DMU except for the Pareto frontier, will have the efficiency of above 100%. Thus the Pareto frontier in DEA models is defined by efficient DMUs. A more detailed account of how this is done is provided by Adler, Friedman, and Sinuany-Stern (2002). However, conventional DEA methods treat the systems under investigation as a *black box* with no further insights into the efficiency of sub-processes within those systems.

To seek transparency into the black box, efficiency of sub-processes were investigated Fare (1991), while some DEA research sought to simultaneously consider both system and sub-process efficiencies (Kao & Hwang, 2008; Sarkis & Talluri, 1996). Part of this investigation involved the utilization of network DEA models.

Network DEA has been applied to a variety of contexts from performance measurement in mostly the banking industry (Akther, Fukuyama, & Weber, 2013; Matthews, 2013) to other industrial and services sectors (Mirhedayatian et al., 2014; You & Jie, In press). Despite its advantages, the application of network DEA models in supply chain performance assessment has been limited to a few studies (Chen & Yan, 2011; Mirhedayatian et al., 2014), which are all associated with manufacturing supply chains rather than service supply chains.

Whereas early DEA models focused on radial approaches to evaluate efficiency (e.g., BCC and CCR models), the SBM approach was later recommended to improve DEA discrimination power (Tone & Tsutsui, 2009). SBM also enables network DEA models to account for weakly efficient DMUs. SBM is a suitable approach where the changes in inputs and outputs are non-proportionate. SBM also allows inputs and outputs of different units of measurement to be incorporated in the DEA model (Cooper, Seiford, & Tone, 2006). In supply chains, this feature of SBM allows analysts the latitude to include data with different units of measurement in one SBM-based network DEA model. Recently, there has been growing interest among operations researchers to adopt the SBM approach in network DEA for different industrial and services contexts due to its accuracy and flexibility (see among, Akther et al., 2013; Fukuyama & Mirdehghan, 2012; Kao, 2014a; Matthews, 2013).

The application of network DEA models are mostly limited to closed systems in which all the variables are known to evaluate the DMUs. Systems in practical settings, supply chains and global supply chains in particular, where outsourcing practices occur, include different players with complex and large numbers of measures and metrics to manage. To this end, Chang et al. (2014) proposed the *ownership-specified* network DEA models. These models introduced input-oriented and output-oriented network DEA models for three types of *centralized*, *distributed*, and *hybrid* network structures. Different proportions of processes were assigned to internal and external entities in supply chains. Integrating hybrid network DEA with variable returns-to-scale and SBM, we discuss how the performance of an outsourcer could be evaluated in supply chains by considering all the input and output processes from both internal and external entities within that supply chain.

Model development

This section presents the analytical model developed to evaluate performance in supply chains with processes related to internal entities, such as divisions, branches, subsidiaries, and to external entities such as suppliers, distributors, wholesalers as hybrid networks (see Figure 2.1). SBM with variable returns-to-scale (Kao, 2014a; Tone & Tsutsui, 2009) is used to enable network DEA models to identify weakly efficient DMUs. The hybrid network modelling approach (Chang et al., 2014) is adopted to incorporate exogenous and endogenous inputs and outputs associated with all the processes in a given supply chain. As previously discussed, one of the main concerns of outsourcing in supply chains is information loss and information asymmetry between tiers in supply chains (Ellram et al., 2008; Handley & Gray, 2013). In reality, it is unlikely for the outsourcer to have access to complete supplier information (inputs and outputs). Chang et al. (2014) proposed ownership-specified network DEA models for such hybrid networks. We subsequently combine this model with general SBM for network systems (Kao, 2014a) providing a more accurate estimation and increased discrimination power of efficiency scores for outsourcers and their supply chains.

The notation and indices are provided in Table 2.7.

Table 2.7 Notations

i= Numerator index corresponding to exogenous inputs
r= Numerator index corresponding to exogenous outputs
f= Numerator index corresponding to endogenous inputs
g= Numerator index corresponding to endogenous outputs
J= Set of DMUs
K= Set of all processes for both external and internal entities
K_I= Set of processes for internal entities
K_E= Set of processes for external entities
$I^{(k_I)}$= Set of exogenous inputs for k_I
$O^{(k_I)}$= Set of exogenous outputs for k_I
$M^{(k_I)}$= Set of endogenous inputs for k_I
$N^{(k_I)}$= Set of endogenous outputs for k_I
$I^{(k_E)}$= Set of exogenous inputs for k_E
$O^{(k_E)}$= Set of exogenous outputs for k_E
$x_{ij}^{(k)}$= ith exogenous input of jth DMU for k

$y_{rj}^{(k)}$= rth exogenous output of jth DMU for k

$z_{fj}^{(k_I)}$= fth endogenous input of jth DMU for k_I

$z_{gj}^{(k_I)}$= gth endogenous output of jth DMU for k_I

$s_i^{(k)-}$ = Input slack variable of ith exogenous input for k

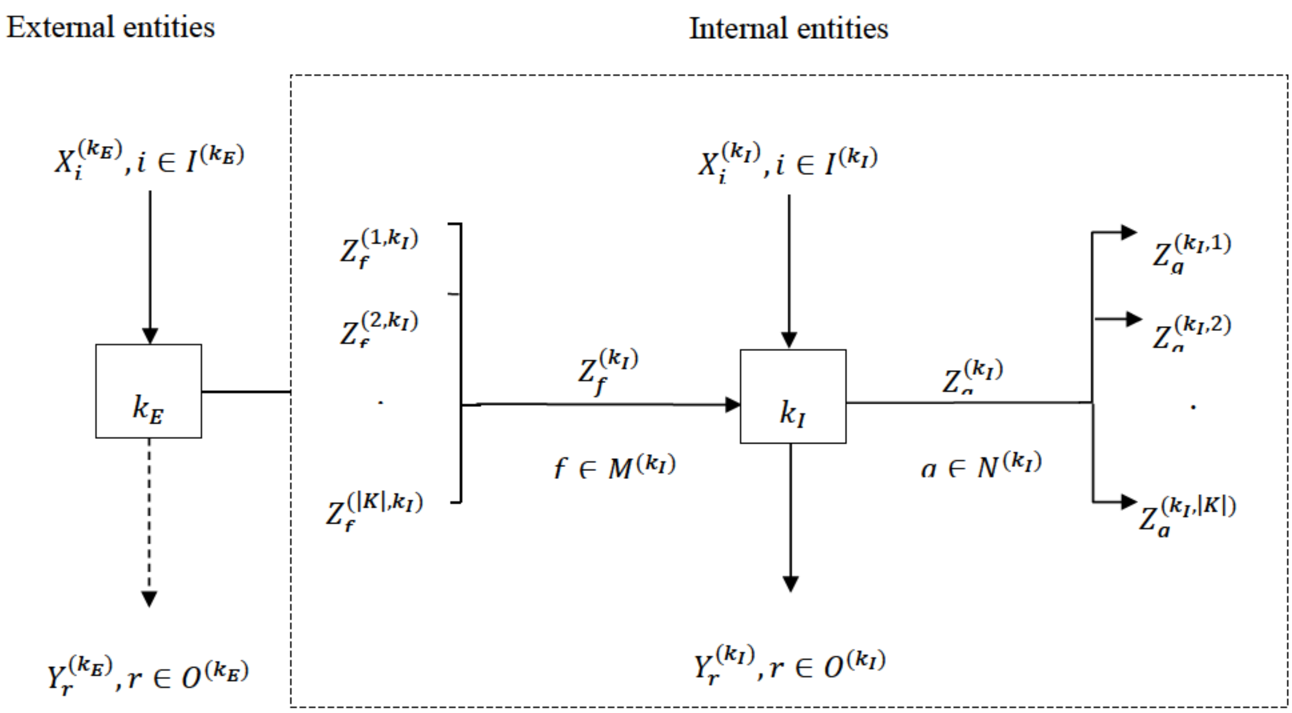
$s_r^{(k)+}$ = Output slack variable of rth exogenous output for k

$t_f^{(k_I)-}$ = Input slack variable of fth endogenous input for k_I

$t_g^{(k_I)+}$ = Output slack variable of gth endogenous output for k_I

Hybrid networks are usually comprised of a total number of $|K|$ entities with a set of $|K_I > 1|$ internal entities and $|K_E \geq 1|$ external entities such that $K_I \cup K_E = K$ and $K_I \cap K_E = \emptyset$ (Chang et al., 2014). In these networks, the main manufacturer or service provider (i.e., outsourcer) has complete control over the processes of its internal entities, while this control is only partial when dealing with external entities such as suppliers or distributors under certain contractual agreements. Usually, the only known parameters to the outsourcer are the endogenous inputs and outputs received from or sent to the supplier in exchange for payments for the goods or services provided by the supplier (i.e., exogenous inputs to supplier). However, accessibility of the outsourcer to the information related to the supplier's extra outputs is highly unlikely. Thus, exogenous outputs ($Y_{rj}^{(k)}$) produced by suppliers (K_E) in Figure 2.6 are illustrated by dotted lines indicating their inaccessibility. It is assumed that an outsourcer's knowledge of the exogenous inputs of processes for external entities is only partial. Thus unlike the exogenous outputs, known exogenous inputs of external entities that directly relate to outsourcing practices are included in the model (Chang et al., 2014). The model can be extended to include downstream external entities as well, but the focus of this article is on the upstream relationships and outsourcing.

Figure 2.6 Supply chain outsourcing model with internal and external entities



Referencing Figure 2.6, let $X_i^{(k)}, i \in I^{(k)}$ be the exogenous inputs and $Z_f^{(k_I)}, f \in M^{(k_I)}$ the endogenous inputs utilized by either one of the internal or external entities in a supply chain to produce endogenous outputs $Z_g^{(k_I)}, g \in N^{(k_I)}$ used by downstream internal or external entities to produce the exogenous outputs $Y_r^{(k_I)}, r \in O^{(k_I)}$. The production probability set $P = \{(x, y, z)\}$ of this network is defined as (Fare & Grosskopf, 2000; Fare et al., 1996):

$$\sum_{j=1}^{n} \lambda_j^{(k)} X_{ij}^{(k)} \leq x_i^{(k)} \left(i \in I^{(k)}; \forall k \in K\right), \quad (1a)$$

$$\sum_{j=1}^{n} \lambda_j^{(k)} Z_{fj}^{(k)} \leq z_f^{(k)} \left(f \in M^{(k)}; \forall k \in K_I\right), \quad (1b)$$

$$\sum_{j=1}^{n} \lambda_j^{(k)} Z_{gj}^{(k)} \geq z_g^{(k)} \left(g \in N^{(k)}; \forall k \in K_I\right), \quad (1c)$$

$$\sum_{j=1}^{n} \lambda_j^{(k)} Z_{gj}^{(k)} = \sum_{j=1}^{n} \lambda_j^{(k+1)} Z_{fj}^{(k)} \left(g \in N^{(k)}; f \in M^{(k+1)}; \forall k \in K_I\right), \quad (1d)$$

$$\sum_{j=1}^{n} \lambda_j^{(k)} Y_{rj}^{(k)} \geq y_r^{(k)} \left(r \in O^{(k)}; \forall k \in K_I\right), \quad (1e)$$

$$\sum_{j=1}^{n} \lambda_j^{(k)} = 1 \, (\forall k \in K), \quad (1f)$$

$$\lambda_j^{(k)} \geq 0 \, (\forall j \in J; \forall k \in K) \quad (1g)$$

where $\lambda_j^{(k)}, j \in J$ is the intensity factor corresponding to the kth process $k \in K$. Equation (1f) implies variable returns-to-scale (Banker, Charnes, & Cooper, 1984). Equations (1a) and (1b) represent feasible exogenous and endogenous inputs for process $k, \forall k \in K$ to be greater than or equal to the convex hull of the existing exogenous and endogenous inputs for that process. Any feasible exogenous outputs for internal entities and endogenous outputs for the processes of all entities in equations (1c) and (1e) should be less than the convex hull of the respective exogenous and endogenous outputs for their respective process. Equation (1d) ensures that continuity of flows between two consecutive processes is maintained, which means that all intermediate products by process k are utilized by process $k+1, \forall k \in K$. It should be noted that based on expression (1e), only exogenous outputs of internal entities known to the outsourcer in its internal processes are needed; thus eliminating unknown exogenous outputs by other members of the supply chain.

Using the general SBM for network DEA models (Kao, 2014a) and the hybrid network DEA model (Chang et al., 2014) in a single model, system efficiency of DMU$_o$ can be formulated as:

$$E_o = min \frac{\sum_{k=1}^{|K|} \left[1 - \left(\sum_{i \in I^{(k)}} \frac{s_i^{(k)-}}{X_{io}^{(k)}} + \sum_{f \in M^{(k_I)}} \frac{t_f^{(k_I)-}}{Z_{fo}^{(k_I)}}\right) \Big/ \left(\hat{\imath}^{(k)} + \widehat{m}^{(k_I)}\right)\right]}{\sum_{k=1}^{|K|} \left[1 + \left(\sum_{r \in O^{(k_I)}} \frac{s_r^{(k_I)+}}{Y_{rp}^{(k_I)}} + \sum_{g \in N^{(k_I)}} \frac{t_g^{(k_I)+}}{Z_{go}^{(k_I)}}\right) \Big/ \left(\hat{o}^{(k_I)} + \hat{n}^{(k_I)}\right)\right]} \quad (2a)$$

$$\sum_{j=1}^{n} \lambda_j^{(k)} X_{ij}^{(k)} + s_i^{(k)^-} = x_{io}^{(k)} \left(i \in I^{(k)}; \forall k \in K\right), \tag{2b}$$

$$\sum_{j=1}^{n} \lambda_j^{(k_I)} Z_{fj}^{(k_I)} + t_f^{(k_I)^-} = z_{fo}^{(k_I)} \left(f \in M^{(k_I)}; \forall k_I \in K_I\right), \tag{2c}$$

$$\sum_{j=1}^{n} \lambda_j^{(k_I)} Z_{gj}^{(k_I)} - t_g^{(k_I)^+} = z_{go}^{(k_I)} \left(g \in N^{(k_I)}; \forall k_I \in K_I\right), \tag{2d}$$

$$\sum_{j=1}^{n} \lambda_j^{(k_I)} Z_{gj}^{(k_I)} = \sum_{j=1}^{n} \lambda_j^{(k_I+1)} Z_{fj}^{(k_I)} \left(g \in N^{(k_I)}; f \in M^{(k_I+1)}; \forall k_I \in K_I\right), \tag{2e}$$

$$\sum_{j=1}^{n} \lambda_j^{(k_I)} Y_{rj}^{(k_I)} - s_r^{(k_I)^+} = y_{ro}^{(k_I)} \left(r \in O^{(k_I)}; \forall k \in K_I\right), \tag{2f}$$

$$\sum_{j=1}^{n} \lambda_j^{(k)} = 1 \; (\forall k \in K), \tag{2g}$$

$$\lambda_j^{(k)} \geq 0, s_i^{(k)^-} \geq 0, t_f^{(k_I)^-} \geq 0, t_g^{(k_I)^+} \geq 0, s_r^{(k_I)^+} \geq 0 (\forall j \in J; \forall k \in K; \forall k_I \in K_I;\ i \in I^{(k)}; f \in M^{(k_I)}; g \in N^{(k_I)}; r \in O^{(k_I)}) \tag{2h}$$

where $s_i^{(k)^-} (\forall k \in K; i \in I^{(k)})$, $t_f^{(k)^-} (\forall k_I \in K_I; f \in M^{(k_I)})$, $t_g^{(k)^+} (\forall k_I \in K_I; g \in N^{(k_I)})$, $s_r^{(k_I)^+} (\forall k_I \in K_I; r \in O^{(k_I)})$ are slack variables associated with (2b), (2c), (2d), and (2f), respectively. Additionally, $\hat{\imath}^{(k)}$, $\hat{m}^{(k_I)}$, $\hat{o}^{(k_I)}$, and $\hat{n}^{(k_I)}$ represent the number of indices in $I^{(k)}$, $M^{(k_I)}$, $O^{(K_I)}$, and $N^{(k_I)}$, respectively.

The slack variables associated with endogenous inputs and outputs are included in system efficiency objective (2a) (Fukuyama & Mirdehghan, 2012; Kao, 2014a). Unlike the traditional SBM approach (Tone & Tsutsui, 2009), there is no need to insert the weight of processes in equation (2a) (Kao, 2014a). Whereas (2a)-(2h) provide a set of weights for each process in a given DMU by defining the process weights as the ratio of output efficiency score of each of the processes over the sum of all other processes in the system. Thus, we ascertain that all the defined weights are positive and they add up to one, as a requirement for the system efficiency being the weighted average of the efficiency of its sub-processes. Hence, upon solving (2a)-(2h) and obtaining optimal solutions for $s_i^{(k)^{-*}}$, $t_f^{(k_I)^{-*}}$, $s_r^{(k_I)^{+*}}$, and $t_g^{(k_I)^{+*}}$ system efficiency and process efficiency for DMU$_o$ can be formulated as:

$$E_o = \frac{\sum_{k=1}^{|K|}\left[1 - \left(\sum_{i\in I^{(k)}} \frac{s_i^{(k)^{-*}}}{X_{io}^{(k)}} + \sum_{f\in M^{(k_I)}} \frac{t_f^{(k_I)^{-*}}}{Z_{fo}^{(k_I)}}\right) \Big/ \left(\hat{\imath}^{(k)} + \widehat{m}^{(k_I)}\right)\right]}{\sum_{k=1}^{|K|}\left[1 + \left(\sum_{r\in O^{(k_I)}} \frac{s_r^{(k_I)^{+*}}}{Y_{rp}^{(k_I)}} + \sum_{g\in N^{(k_I)}} \frac{t_g^{(k_I)^{+*}}}{Z_{go}^{(k_I)}}\right) \Big/ \left(\hat{o}^{(k_I)} + \hat{n}^{(k_I)}\right)\right]}, \tag{3a}$$

$$E_o^{(k)} = \frac{1 - \left(\sum_{i\in I^{(k)}} \frac{s_i^{(k)^{-*}}}{X_{io}^{(k)}} + \sum_{f\in M^{(k_I)}} \frac{t_f^{(k_I)^{-*}}}{Z_{fo}^{(k_I)}}\right) \Big/ \left(\hat{\imath}^{(k)} + \widehat{m}^{(k_I)}\right)}{1 + \left(\sum_{r\in O^{(k_I)}} \frac{s_r^{(k_I)^{+*}}}{Y_{rp}^{(k_I)}} + \sum_{g\in N^{(k)}} \frac{t_g^{(k_I)^{+*}}}{Z_{go}^{(k_I)}}\right) \Big/ \left(\hat{o}^{(k_I)} + \hat{n}^{(k_I)}\right)} \quad (\forall k \in K;\ \forall k_I \in K_I), \tag{3b}$$

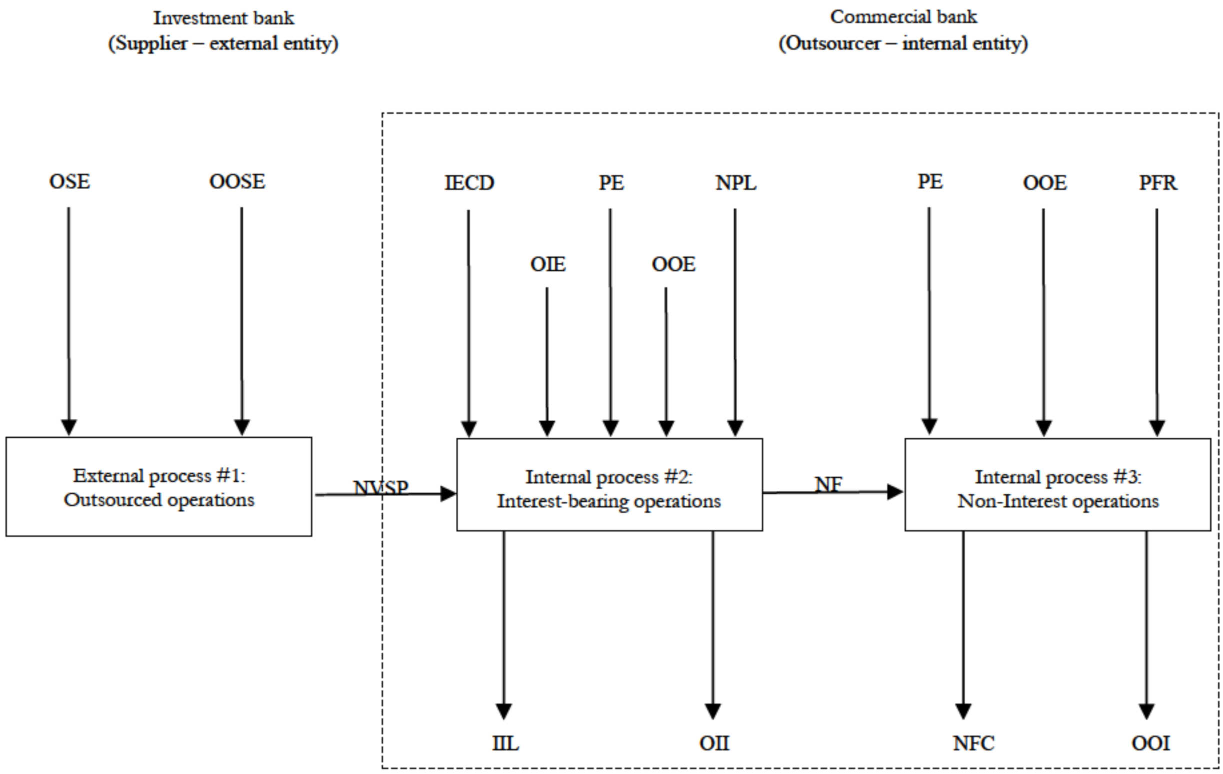
Chang et al. (2014) argue that due to the lack of information about the processes in external entities, reporting their efficiency scores using equation (3b) is not recommended. However, these external entities and their interaction with the internal entities in supply chains should be considered for evaluating the performance of the outsourcer and obtaining the overall supply chain efficiency. This is achieved in our proposed models (2a-2h) and (3a-3b) by incorporating the relevant inputs/outputs of suppliers, as external entities, to outsourcer's operations.

A case study from the banking industry

The service industry deals directly with customers. Quality is immediate and can have an instant effect on the bottom line of service settings. An important aspect of quality in service industry is making sure that efficient and timely service is provided. Thus, efficiency of processes, whether internal or outsourced is a major driver for quality.

We consider a service supply chain comprised of a commercial bank and its subdivisions as internal entities and operations related to an investment bank collaborating with the commercial bank as an external entity. Commercial banks provide a variety of banking services such as loans and other credit products, trade finance, specialized employer and cash management services, and corporate financing through issuing and underwriting bonds. Services provided to commercial banks' corporate customers through their corporate banking division fall into two main categories, interest-bearing and non-interest bearing services (Avkiran, 2015). While lending and revenues obtained from loans are the main function of the interest-bearing services, commissions from other financial services such as bonds underwriting and issuing services constitute a commercial bank's main non-interest revenues. Figure 2.7 illustrates the service supply chain of commercial banks as outsourcers of certain financial services to external investment banks.

Figure 2.7 Service supply chain of commercial banks with two internal entities and one external entity



Legend: OSE (outsourcing expenses), OOSE (other outsourcing expenses), NVSP (net value of services provided), IECD (interest expense on customer deposits), OIE (other interest expenses), PE (personnel expense), OOE (other operating expense), NPL (non-performing loans ratio), IIL (interest income on loans), OII (other interest income), NF (number of referrals), PFR (proportion of fruitless referrals), NFC (net fees and commissions), OOI (other operating income).

A commercial banking performance model is adopted for this study Avkiran (2015). A single financial period is used to assign inputs and outputs on *Non-interest operations* and *Interest-bearing operations* divisions, which will be considered internal entities of the service supply chain. Sometimes commercial banks collaborate with or outsource certain financial services to external investment banks, especially for large financing projects. Outsourcing expenses, such as commissions, costs of quality of services, and supervisory costs, could be considered exogenous inputs. Net value of services provided is the endogenous output of the external investment bank for the commercial bank.

A variety of financial and non-financial performance measurement criteria in the supply chain literature for evaluating the quality of outsourcing exist (Gunasekaran et al., 2015). In this study we rely on the well-established frameworks proposed for bank efficiency assessment in the DEA literature to ensure the validity of the performance metrics (Fethi & Pasiouras, 2010).

The performance metrics in this model include good and bad outputs. For example *Proportion of fruitless referrals* and *Non-performing loans ratio*s may be outcomes that are perceived as bad outputs and can be treated as inputs in the formulation of the model in (2a)-(2h) (Avkiran, 2015; Thanassoulis, Portela, & Despic, 2008).

The context of the case study is commercial banks' service supply chains in Iran. Iran's less-investigated banking and financial market has recently drawn attention of foreign investors. The Iranian banking system plays an important role in providing financial services to different industrial and service sectors in this country. Iran started introducing private banks to its financial market in the late 1990s. Over the past decade, in addition to some newly established private banks, shares of former public banks, such as Mellat and Tejarat, have been offered on the Tehran Stock Exchange. Currently, eight public banks, 21 private banks and six other financial and credit institutions are active in Iran's financial market. According to the reports published by regulatory bodies in Iran, by November 2013 the value of loans to individuals and commercial customers for private banks alone extended 46 billion USD, which is a significant amount given Iran's economy. However, despite their significance, private banks are performing weaker than public banks in converting deposits to loans. Moreover, private banks have a relatively smaller share of deposits than public banks but perform better in the domains of online and mobile banking. Since 2007 and after the introduction of universal banking systems in Iran, private sector commercial banks have made significant advancements in the variety and quality of services they provide.

Given a highly competitive environment where banks seek to acquire larger market share, public and private commercial banks in Iran look for ways to best estimate the efficiency of their sub-divisions and their collaborating suppliers that include other investment banks and financial institutions.

Data for this study is acquired through the use of archival data published in the periodical reports of the Central Bank of Iran, *Annual Review*, and through field study visits to commercial banks' information and customer service centres. The data collection focused on the sets of inputs and outputs necessary for the model as defined in Figure 2.7. Table 2.8 summarizes the descriptive statistics of the exogenous and endogenous inputs and outputs used in this study. A total of 28 public and private commercial banks in Iran had data that could be used in the analysis. MATLAB 2014b was used to code and execute the models (2a-2h) and (3a-3b).

Table 2.8 Descriptive statistics of exogenous and indigenous inputs and outputs for financial year 2013–2014[a]

	Factor	Mean	Standard Deviation	Minimum	Maximum
Outsourced operations (External process #1)					
Outsourcing expenses	x_{1j}^{1}	13.314	7.499	5.999	23.793
Other outsourcing expenses	x_{2j}^{1}	6.278	2.997	4.339	10.748
Net value of services provided	z_{1j}^{1}	20.099	3.067	16.217	23.582
Interest-bearing operations (internal process #2)					
Interest expenses on consumer deposits	x_{1j}^{2}	109.601	16.039	88.523	125.860
Other interest expenses	x_{2j}^{2}	46.823	10.468	33.709	58.593
Personnel expenses	x_{3j}^{2}	35.689	11.429	20.091	47.357
Other operating expenses	x_{4j}^{2}	48.009	6.594	33.664	63.966
Non-performing loans ratio	x_{5j}^{2}	0.051	0.030	0.225	0.091

	Factor	Mean	Standard Deviation	Minimum	Maximum
Interest income on loans	y_{1j}^2	456.596	127.486	331.136	578.740
Other interest income	y_{2j}^2	133.915	39.278	91.162	168.683
Number of referrals	z_{1j}^2	83.625	18.065	61.250	101.500
Non-interest operations (internal process #3)					
Personnel expenses	x_{1j}^3	26.284	7.096	17.593	32.222
Other operating expenses	x_{2j}^3	42.129	9.498	30.715	52.418
Proportion of fruitless referrals	x_{3j}^3	0.087	0.014	0.071	0.105
Net fees and commissions	y_{1j}^3	36.604	10.087	22.383	46.207
Other operating income	y_{2j}^3	19.444	3.874	14.050	23.116

[a] Financial data is in USD million.

Results and discussion

Parametric and non-parametric statistical tests for the efficiency scores obtained by the model (presented in section "*Model development*", page 73) are summarized in Table 2.9. The results show that commercial banks of the public sector are equally efficient as the private sector in their overall efficiency and non-interest operations efficiency (i.e., *Internal process #3*). However, a significant gap in the efficiency of the interest-bearing operations (i.e., *Internal process #2*) is observed when comparing public and private banks. Public banks for internal process #2 show better performance. This result implies a higher ratio of interest income to expenses for public banks. The statistically significant lower mean for private commercial banks interest-bearing operations efficiency scores are likely caused by newly-established private banks such as Khavarmianeh and Ansar banks.

As previously discussed, investment bank efficiency scores (i.e., *External process #1*) were not included since banks, as outsourcers, did not have enough access to all the financial criteria required to conduct a holistic evaluation of those external entities. However, investment bank impact on commercial bank performance is evaluated through the commissions and other operational expenses investment banks charged commercial banks for services they provided.

Table 2.9 Efficiency scores for the overall service supply chain and for internal processes

No.	DMU	Overall supply chain efficiency	Rank	Efficiency of internal process #2	Efficiency of internal process #3
	Public commercial banks				
1	Sepah	0.774	21	0.862	0.799
2	Post Bank	0.837	20	0.696	0.903
3	Melli Iran	1	1	1	1
4	Tose-e-Saderat	0.967	17	0.956	0.877
5	Sanat-va-Madan	0.739	22	0.909	0.684
6	Keshavarzi	1	1	1	1
7	Maskan	1	1	1	1
8	Tose-e-Taavon	0.988	16	0.962	0.967
	Mean for public banks	0.913		0.923	0.904
	Number of efficient public banks	3		3	3
	Private commercial banks				
1	Eghtesad Novin	1	1	1	1
2	Parsian	1	1	1	1
3	Kaar Afarin	0.995	14	1	0.947
4	Saman	0.937	19	0.844	0.981
5	Pasargad	1	1	1	1
6	Sarmaye	1	1	1	1
7	Sina	1	1	1	1
8	Shahr	0.993	15	0.974	1
9	Day	0.683	23	0.755	0.605
10	Ansar	0.573	26	0.229	0.590
11	Tejarat	1	1	1	1
12	Refah-e-Kargaran	0.960	18	0.936	0.845
13	Saaderate-e-Iran	0.683	23	0.558	0.836
14	Mellat	1	1	1	1
15	Hekmat-e-Iranian	1	1	1	1
16	Gardeshgari	0.388	27	0.598	0.221
17	Iran Zamin	0.630	25	0.988	0.452
18	Ghavamin	1	1	1	1
19	Khavarmianeh	0.206	28	0.500	0.680

No.	DMU	Overall supply chain efficiency	Rank	Efficiency of internal process #2	Efficiency of internal process #3
	Public commercial banks				
20	Ayandeh	1	1	1	1
	Mean for private banks	0.852		0.847	0.867
	Number of efficient private banks	10		11	12
	T-test (p-value, two-tailed)	0.681 (0.502)		2.613 (0.015)*	0.557 (0.582)
	Mann-Whitney U (Prob > X2, one-tailed)	79 (0.481)		15 (0.000)*	71.5 (0.326)
	Wilcoxon W (Prob > X2, one-tailed)	115 (0.481)		51 (0.000)*	107.5 (0.326)

* Significant at 0.05 level.

Figures 2.8 and 2.9 graphically illustrate the differences between public and private bank overall efficiency scores and efficiency scores of internal processes #2 and #3, respectively. There is no direct pattern in differences, where the overall efficiency score for a commercial bank's service supply chain is higher than the efficiency scores of its sub-processes in some cases, whereas in others it is lower. These inconsistencies could be traced back to the role of the external entities, such as the investment bank in this example. In some cases such as Tose-e-Taavon bank (labelled '8' in Figure 2.8) efficiency in the processes of the external investment bank has resulted in an overall higher efficiency score of the bank's supply chain compared to the efficiency of its internal processes. In other cases such as Sepah bank (labelled '1' in Figure 2.8), an opposite result was observed; where overall efficiency score has suffered from inefficiencies in the operations of its investment bank. One of the possible causes of this inefficiency could be traced back to comparatively higher amounts of expenditure made to provide the same value of services by investment banks for the commercial banks. Thus, although no direct patterns existed, banks can complete a relative analysis of how outsourced activities have affected the efficiency, and quality, of their performance. One way of doing this is to evaluate overall efficiency versus internal process efficiency, where higher overall efficiencies when compared to internal efficiencies, implying better outsourcing quality performance.

The same pattern could be observed for private commercial banks' service supply chains. For instance, while Refah-e-Kargaran bank (labelled '12' in Figure 2.9) shows a higher overall efficiency than its internal processes, Khavarmianeh bank's efficiency scores (labelled '19' in Figure 2.9) reveal that there could have been serious inefficiencies in the operations with its collaborating, outsourced, investment bank.

For the remainder of the cases in which overall efficiency scores are between the efficiency scores of the internal processes, this could be an indicator of the operations of external investment banks being aligned with the internal operations of the banks. It is worth mentioning that if a conventional network DEA model was adopted for this case, the results would have overlooked the impact of an external entity, in this case an investment bank, on the operations of the bank as an outsourcer.

Figure 2.8 Comparison of efficiency scores for public banks

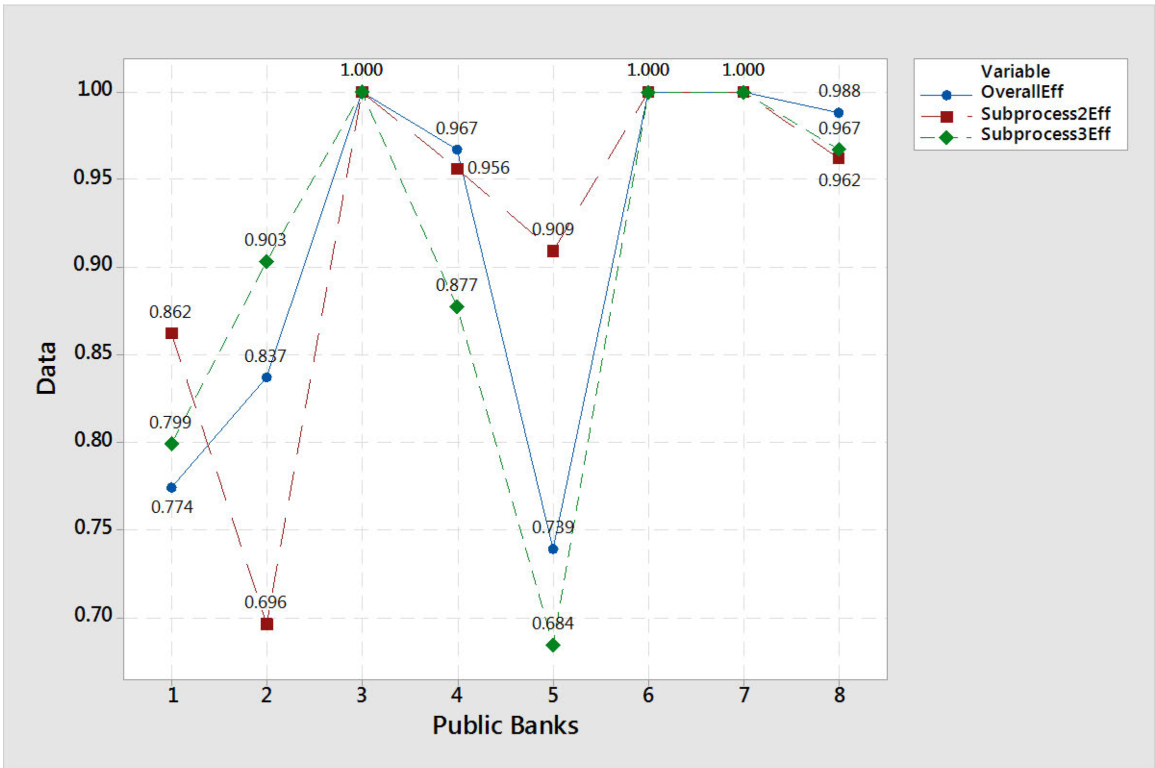
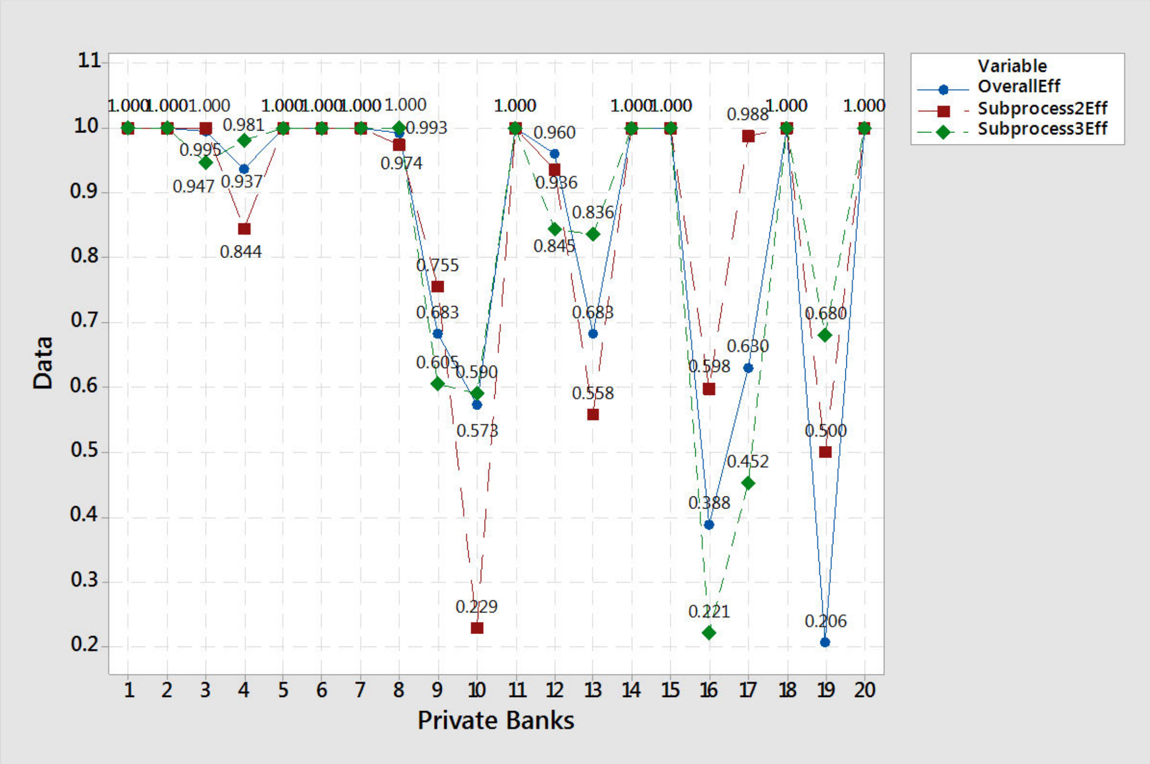


Figure 2.9 Comparison of efficiency scores for private banks



Robustness check and sensitivity analysis

In this study, the commercial bank service supply chain included 16 exogenous and endogenous inputs and outputs for its external and internal processes. As a rule of thumb, this requires at least 16*3=48 DMUs to ensure that the model will show sufficient discrimination power (Sarkis, 2007). It has been recommended that the total number of DMUs in network DEA models are multiplied by the number of sub-processes that are being investigated (Kao, 2009). Thus, having 28 DMUs and three processes (28*3=84) satisfies the criterion for the number of DMUs required to conduct the analysis. Similar to traditional DEA, greater sample size will result into greater discrimination (Avkiran & McCrystal, 2012).

The robustness of the proposed model is tested by switching from a variable returns-to-scale to a constant returns-to-scale, and then excluding the investment bank from the original model. Constant returns-to-scale offers more discrimination power than variable returns-to-scale because fewer DMUs appear on the efficient frontier. After this robustness check, the final range of the efficiency scores for the overall supply chain and for the internal processes remained almost the same.

Second, excluding the investment bank data from the model in Figure 2.7 showed a marginal increase in the efficiency scores of the overall supply chain and for the internal sub-processes. This result further confirms that excluding external influential factors in measuring the efficiency of the outsourcer (i.e., the investment bank) could overestimate its performance and lead to computational biases.

Model evaluation

The network DEA model used in this study shows how performance could be evaluated in outsourcing supply chains, where there is insufficient information about the supplier operations whilst their performance do affect outsourcers operations. The novel combination of an SBM approach and network DEA model, first introduced in this study, integrates relevant information of external entities to use in the final performance evaluation of the outsourcer's processes. The proposed combined model offers greater discrimination power amongst DMUs when compared to conventional network DEA models. The new model is capable of assessing several sub-processes in addition to overall supply chain efficiency. More accurate estimations of supply chain inefficiency sources could aid supply chain managers and decision makers to more effectively address those inefficiencies, enhancing quality of their goods and services. This issue becomes especially important in service supply chains in which there is greater direct interaction with customers. Poor quality of services in these supply chains could have a greater risk of outsourcer losing customers and incurring financial losses. Although, the measures used in the case example of this study were based on financial information and data for performance evaluation, the proposed analytical model could be generally applied in different manufacturing and service contexts, using broader variety of quality and business performance metrics.

Conclusions

Despite outsourcing strategies being widely adopted by firms around the globe, studies on organizational performance in supply chains resulting from and guiding outsourcing decisions are relatively scarce. This scarcity is even more evident in the context of service supply chains. Outsourcing management in service supply chains offers much room for improvement when compared to the more traditional manufacturing supply chains.

Given the calls for more investigations on quality issues in outsourcing, this study presented an analytical model using a combined SBM and network DEA model. The approach enables outsourcers to identify inefficiency sources using data on both internal and external entity processes. To help with validation and analysis, the model was applied to the commercial banking context in Iran. The analysis shows how performance of several public and private commercial banks and their service supply chain can be evaluated. Statistical inference testing of the results showed differences in performance of public and private banks interest-bearing operations. The results also showed how outsourcing to external entities could influence the overall efficiency of a supply chain, either positively or negatively.

This article contributes to the outsourcing and supply chain management literature by evaluating a significant set of processes in internal and external entities. The processes can be evaluated using multiple factors that could affect quality and performance in supply chains that outsource their operations to external entities. The hybrid network DEA model introduced in this study incorporates exogenous and endogenous inputs and outputs used to prepare the final product or service offered by an outsourcer. By combining the hybrid network DEA model with a general SBM approach, limitations of traditional network DEA models in terms of pre-specification of weights for processes and relatively low discrimination power of these models were eliminated. SBM also enables the network DEA models to account for weakly efficient DMUs, hence increasing the accuracy of the results.

The analytical model presented in this study is applicable to a larger context of manufacturing and services supply chains with flexibility for performance measurement metrics selected. The model is mostly suitable when there is information asymmetry between different tiers in supply chains and when the outsourcer's knowledge and understanding of the processes related to external upstream or downstream supply chain members are limited.

This study has limitations. The inputs and outputs of the presented model involve merely quantifiable and financial criteria that are more accessible and easy to measure. However, for qualitative assessment criteria (e.g., Srinivasan & Kurey, 2014) to be incorporated in the model, more sophisticated approaches such as fuzzy network DEA (Kao, 2014c) could be leveraged to address the uncertainties associated with the aforementioned criteria. We suggest the application of α-cut approach (Kao & Liu, 2011). First, triangular fuzzy numbers of inputs, outputs and the intermediate products need to be developed. Next, upper bound and lower bound of the α-cut of E_o (2a-2h) need to be calculated for different values of α varying between 0 and 1. At $\alpha = 0$ the range of all possible efficiency scores for different values of α is determined. Moreover, at $\alpha = 1$, the most likely efficiency score for the DMUs is obtained. Despite additional discrimination power of the DEA model when combined with the SBM measure, the number of DMUs needs to be significantly larger than basic DEA models to ensure that the results have sufficient discrimination power.

Future research can focus on incorporating into the model both behavioural and operational factors that could affect quality of outsourced supply chains. In general, including behavioural factors in analytical models of operations and supply chain management results in better predictability and compliance of these models to operating systems (Giannoccaro & Ilaria, 2013). Moreover, the latter could specifically enhance the precision of analytical models (e.g., supply chain performance measurement models) that are used to make managerial decisions (Hämäläinen, Luoma, & Saarinen, 2013; Tiwana, Wang, Keil, & Ahluwalia, 2007). For instance the level of trust (Brinkhoff, Özer, & Sargut, 2015a; Brinkhoff, Özer, & Sargut, 2015b) between the outsourcer and supplier is a proven detrimental factor affecting final products and services characteristics delivered by the supply chain. In fact, a variety of behavioural criteria in intra-organizational and inter-organizational relations (Bendoly, Croson, Goncalves, & Schultz, 2010; Gino & Pisano, 2008a) could be prioritized and included in the proposed model, which in turn could offer a better understanding of quality issues in outsourcing supply chains.

It is nevertheless worth mentioning that such approaches are generally considered to be making the mathematical models even more complex and sometimes difficult to solve (Mingers, 2011). This assumption however has been revisited by Bendoly, Donohue, and Schultz (2006, p. 739), p. 739 who argue that "the two methodologies [i.e., mathematical models of operations and methods used for studying human behaviour] can complement each other with each positing useful directions of inquiry for the other". In fact, Bendoly, van Wezel, and Bachrach (2015) suggests that such mixed models introduce new opportunities to better comprehend and manage operations within a given context. The application of multi-methods is hence strongly recommended to first obtain the behavioural data using laboratory and field experiments and then aggregate the behavioural data with quantitative data for incorporation into the model (Bendoly & Eckerd, 2013; Choi, Cheng, et al., 2016). More advanced models may also be required to better express the hierarchical structure of companies and the internal structures of DMUs.

The proposed model in this study was developed to assess quality of performance for outsourcing in service supply chains. The use of this model in more operational and manufacturing contexts requires to primarily revisiting the inputs, outputs, and intermediate products in the manufacturing supply chain such as production and procurement facilities, speed to market, safety, etc. (for a full list of relevant metrics see, Gunasekaran et al., 2015). Another issue to consider here is that a more realistic account of network structures has been argued to be triadic structures for both manufacturing and service supply networks (Choi & Wu, 2009a; Niranjan & Metri, 2008a). A triadic structure for both manufacturing and service contexts has its unique characteristics in terms of the interconnections between the triad members, which should be taken into account while developing the performance assessment models such as different variations of network DEA.

Overall, this study provides some additional foundation for modelling and evaluation of outsourcing services, especially from a quality perspective. Evaluation and benchmarking with respect to cost, flexibility, time, and other measures can be easy extensions as long as data is available. Given the importance of outsourced activities and internal process implications, data that helps integrate and link the broader supply chain will need to be captured. Tools such as the one provided here can help organizations identify performance measures and relevant analytical models within the outsourcing context. Setting this foundation, ample opportunities for future research exist; not only in this context, but in more general context of performance evaluation of outsourced activities.

2.5. Chapter summary and conclusion

This chapter presented three studies aiming at identifying and assessing operational risks in supply chains. The first paper was systematic review of the literature for supply chain risk identification. The paper presented 10 main operational risk groups with a total number of 58 risk indicators that could adversely affect operations in supply chains.

The second study used a more customized operational risk framework in supply chains consisting of five main groups of risks that could affect inter-/intra-organizational operations in supply chains. The main purpose behind adopting such a framework was to bridge between operational risk and resilience factors in supply chains. Using the network DEA framework proposed in the paper and the survey data, it was found out that tier-specific resilience in supply chains should be investigated in tandem with system-wide resilience to risks in supply chains.

To affirm the findings by the previous study, the third paper specifically adopted the similar analytical framework to show the outsourcing risks in supply chains should also be measured from a tier-specific and system-wide points of view. In the same paper the authors also draw attention to this possibility that the inclusion of behavioural anomalies of decision making alongside the operational risks associated with them could enhance the accuracy of analytical models for supply chain risk assessment. This has been investigated in more details in chapter 3.

-CHAPTER THREE-

-Behavioural Risks in Supply Chains-

3.1. Introduction

While the operations view of supply chain risks identifies and evaluates more tangible risk sources emerging and propagating in supply chains, the behavioural view seeks the root causes lying behind those types of risks that have a human factor in them. Behavioural operations/supply chain management is an attempt to understand the bounded rationality observed in human behaviour through the lenses of cognitive limitations, social preferences, cultural norms, group/system dynamics and adopting this understanding to improve operations within one or multiple organizations (Bendoly et al., 2010; Bendoly et al., 2006; Croson, Schultz, Siemsen, & Yeo, 2013). There have been earlier reviews (Bendoly et al., 2006; Gino & Pisano, 2008b; Loch & Wu, 2007) on behavioural operations management that help better understanding the mediating role of behavioural factors to explain the inconsistencies between empirical findings and the theoretical predictions originally based on the assumption of humans as fully rational agents.

This chapter consists of two main studies. The first paper is among the few attempts in the supply chain management literature to provide an analytical framework for supply chain performance assessment considering several operational indicators and behavioural risks. The analytical model is the same as the papers in Chapter 2, however this time the behavioural factors are also included in the model.

The second paper in this chapter revolves mainly around the attitudes of supply chain decision makers toward risk and how it affects their ordering behaviour. Specifically, risk aversion, risk seeking and loss aversion models are investigated.

3.2. Paper 4: Behavioural and operational risks in supply chains[5]

Investigating the Impact of Behavioural Factors on Supply Network Efficiency: Insights from Banking's Corporate Bond Networks

Abstract

This paper highlights the role of behavioural factors for efficiency measurement in supply networks. To this aim, behavioural issues are investigated among interrelations between decision makers involved in corporate bond service networks. The corporate bond network was considered in three consecutive stages, where each stage represents the relations between two members of the network: issuer-underwriter, underwriter-bank, and bank-investor. Adopting a multi-method approach, we collected behavioural data by conducting semi-structured interviews and applying the critical incident technique. Financial and behavioural data, collected from each stage in 20 corporate bond networks, were analysed using fuzzy network data envelopment analysis to obtain overall and stage-wise efficiency scores for each network. Sensitivity analyses of the findings revealed inefficiencies in the relations between underwriters-issuers, banks-underwriters, and banks-investors stemming from certain behavioural factors. The results show that incorporating behavioural factors provides a better means of efficiency measurement in supply networks.

Keywords: Behavioural operations, corporate bonds service network, network data envelopment analysis, fuzzy sets

Introduction

Although the subject of behaviour has long been popular among organizational, managerial, and business fields of study (e.g., strategy, marketing, economics, and finance), certain aspects of behavior have been introduced quite recently into the operations and supply chain management domain for modelling relevant real-world

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[5] Pournader, M., Kach, A. P., Razavi Hajiagha, S. H., & Emrouznejad, A. Investigating the Impact of Behavioral Factors on Supply Network Efficiency: Insights from Banking's Corporate Bond Networks. *Annals of Operations Research (Rank A)*. (Under review).

situations (Bendoly et al., 2010, p. 79; Croson et al., 2013). Behavioural factors, which reside in behavioural irrationalities embedded in individuals' choices, social preferences, or bounded rationalities (Özer & Zheng, 2012), can result in biased judgments and erroneous decision making. Understanding these behavioural irrationalities is essential if we are to manage them effectively in supply chains (Carter, Kaufmann, & Michel, 2007). Moreover, it has been argued that behavioural factors play an important role in causing several supply chain-related problems (e.g., bullwhip effects), even when almost all other sources of operational errors are eliminated (Croson, Donohue, Katok, & Sterman, 2014; Wan & Evers, 2011).

Including behavioural factors in supply chain decision-making models results in better predictability and more effective operating systems (Giannoccaro & Ilaria, 2013). The latter could especially enhance the predictability of empirical and analytical models that aim to improve decision-making processes (Hämäläinen et al., 2013; Tiwana et al., 2007). However, such approaches are generally overlooked because the aforementioned analytical models are considered too complex to solve (Mingers, 2011). Nonetheless, Bendoly et al. (2006, p. 739), p. 739 argue that, despite the seemingly different assumptions between mathematical models of operations and methods used for studying human behaviour, "the two methodologies can complement each other with each positing useful directions of inquiry for the other". Bendoly et al. (2015) also argue that considering the bounded rationalities of decision makers in mathematical models of operations opens up new avenues and opportunities to better comprehend and manage operations within a given context. That said, managers and researchers alike would benefit from a greater understanding of how behavioural factors play a role in decision-making processes in supply networks and, likewise, the effect they have on supply network efficiency.

Following the call for "high-quality research that is able to influence both thought and practice" surrounding the "human factor" in the field of supply chain management Fawcett, Waller, and Bowersox (2011), p. 119, we focused on including behavioural factors in data envelopment analysis (DEA) models for measuring efficiency in supply networks. DEA models encompass a wide spectrum of applications in industry and services to tackle various aspects of efficiency measurement in supply networks (e.g., Chen & Yan, 2011; Talluri et al., 2013; Wu & Olson, 2009). Our study looked particularly at supply networks within the banking industry, describing a three-stage supply chain process for issuing corporate bonds. Our motivation to investigate the banking industry was twofold. First, of all business sectors, the banking industry is believed to have the highest rate of application of DEA models (Liu et al., 2013b; Wu & Birge, 2012), offering established and validated approaches to model building and efficiency measurement in this context (Paradi & Zhu, 2013). Second, close interactions between decision makers in the banking industry and corporate bond networks during the bond issuing and underwriting processes could potentially expose this network to substantial behavioural risks. Thereby, the purpose of this study was to provide evidence of how behavioural factors influence the efficiency of supply networks by considering the efficiency of both operational and decision-making processes throughout different stages of a supply network, and by leveraging a multi-method approach that encompassed both semi-structured interviews and DEA.

The remainder of this study is organized as follows. Next, we review the literature on the application of behavioural sciences in supply networks, focusing specifically on several behavioural misconducts and their adverse consequences in corporate bond service networks. The summary of the application of network DEA in different industrial and service contexts in the literature review section leads to description of a fuzzy network DEA model developed for the three-stage corporate bond network. In the methodology section we also explain the application of semi-structured interviews and critical incident technique to collect data related to behavioural factors in the corporate bond network. We then incorporate both behavioural and financial data into the fuzzy network DEA model, discussing the numerical outcomes of applying the proposed model to the banking industry of Iran, and examining the robustness of the results. Finally, we summarize the highlights of the study, outline its limitations and note avenues for future research.

Literature review

The study of behavioural issues in operations and supply chain management discourse is an emerging, multi-disciplinary field that is gaining increasing momentum (Bendoly et al., 2010; Knemeyer & Naylor, 2011). One of the main reasons for this growing interest is that current models of real-world processes often fail to reflect human behaviour, despite being one of the main drivers in operating systems (Bendoly et al., 2015; Giannoccaro & Ilaria, 2013). Studying behavioural factors in the context of supply chains and supply networks is described as "the study of how judgment in supply management decision-making deviates from the assumptions of homo economicus" (Carter et al., 2007, p. 634, p. 634). Investigating behavioural factors associated with decision-making processes within the context of inventory management (e.g., newsvendor problem (Nagarajan & Shechter, 2014; Su, 2008), bullwhip effects, and supply line underweighting (Croson et al., 2014; Wang, Ma, et al., 2014)) has helped further explain deviations in efficiency that could not be described from taking a solely operational point of view.

Research into behavioural operations and supply chain management has offered opportunities for investigating decision makers' behaviour, mostly based on cognitive psychology (Gino & Pisano, 2008a; Katsikopoulos & Gigerenzer, 2013). For instance, loss aversion and risk aversion biases have been used primarily for inventory management problems such as the newsvendor problem to model managers' decision-making behaviour (Agrawal & Seshadri, 2000; Wang & Webster, 2009). Studies have also investigated other types of cognitive biases, or even more general estimations of cognitive abilities of decision makers, and their impact on supply chain-related operations (Narayanan & Moritz, 2015; Wu & Chen, 2014). Some researchers have studied the effect of trust between members of supply chains (Özer, Zheng, & Ren, 2014; Read, Jin, & Fawcett, 2014). Others have emphasized psychological aspects such as social psychology, group dynamics, or system dynamics in the context of behavioural operations and supply chain management (Bendoly, 2014; Bendoly et al., 2010). The breadth of previous research illustrates that behavioural issues can affect efficiency in supply networks either at the level of individual decision makers or through their interactions with other individuals, groups, or even organizations. While it is impossible to capture all the behavioural facets for a specific context, we next propose several decision making-related scenarios in corporate bond networks in which certain behavioural anomalies could occur and have an adverse effect on tier-specific and/or overall efficiency of the network.

Behavioural factors emerging and propagating in the corporate bond network

The corporate bond underwriting and issuance network consists of corporate clients as "issuers", investment banks or corporate banks as "underwriters", and "investors" as buyers of the bonds. Underwriters and commercial banks provide bonds issuing and underwriting services such as insurance for the unsold bonds and other types of services associated with pricing, marketing, documenting, and selling the bonds (Yasuda, 2005, 2007). For their existing corporate clients, commercial banks opt for either their own corporate banking division or investment bank(s), or both, as underwriter(s) of corporate bonds.

However, several behavioural factors involved in the bilateral relations of network members could adversely affect the efficiency of operations within the network. For instance, in underwriter-issuer relations, different types of risks might arise if there is no previous history of constructive and collaborative relations between the bank and the corporate client. According to goal-setting theory (Latham & Locke, 1991; Locke & Latham, 2002), when building up good relations with clients is not a unanimously accepted goal among employees, there is insufficient motivation in the organization to put much effort and investment into strengthening relations with corporate customers. Even if banks accept specific and detailed goals regarding how corporate clients should be treated, the absence of salient and timely control mechanisms (i.e., Control Theory; (Bandura, 1989, 2001) could fail to regulate the bank employees' behaviour toward their corporate clients, leading to diminishing quality of services for clients and deteriorating relations between bank and client. Subsequently, clients are prone to assume (Mussweiler & Strack, 2001; Tversky & Kahneman, 1974) that further similar collaborations with the bank, including bonds underwriting and issuance, could yield the same undesirable results. This lack of trust between bank and client imposes additional costs on the bank to improve relations with the corporate client (Friend & Johnson, 2014).

The efficiency of the underwriting process also depends upon how the underwriter and the bank interact. A commercial bank's decision makers may choose an underwriter based on financial incentives; however, a number of behavioural factors could also come into play. First, both opting for an external investment bank as an underwriter and lack of trust between the bank and the investment bank would increase the bank's supervisory costs in eliminating any opportunistic behaviour by the investment bank (Villena, Revilla, & Choi, 2011; Wathne & Heide, 2000). The likely opportunistic behaviour of the investment bank as the supplier of financial services could be reflected in the investment bank offering superior services or significant discounts to the issuer. Second, banks' decision makers might overestimate (Bazerman & Moore, 2012; Moore & Healy, 2008) the ability of the underwriter (especially their own corporate banking division) to provide quality services to their corporate clients. This overestimation might result in poor-quality services, customer dissatisfaction, and unsold bonds.

Bank-investor relations are also subject to risks from behavioural factors. Considering loss-aversion bias, for instance (Kahneman, Knetsch, & Thaler, 1991), the behaviour of a bank's decision makers toward investors could depend on how these decision makers define and perceive losses and gains in their relations with issuers. Corporate banks that are making inroads into the corporate bonds market usually tend to charge issuers with lower fees for the costs of underwriting and issuance services (Gande, Puri, & Saunders, 1999; Yasuda, 2005), with the aim of building good relations with existing issuers and to avoid losing their existing corporate clients at any cost. However, these generous offerings might subsequently culminate in charging the investors higher prices for bonds to compensate for any financial losses (Yasuda, 2007). Moreover, banks that are reluctant to lose their corporate clients at any cost might misuse their reputation in certifying the issuers' quality of bonds for less informed investors (Andres, Betzer, & Limbach, 2014; Mathis, McAndrews, & Rochet, 2009). Such issues could affect investors' trust and willingness to purchase the bonds.

Given the complexity of decision-making processes in real-world supply networks (e.g., corporate bond network), behavioural misconduct can extend beyond what has been discussed thus far. However, irrespective of their origin, poor-quality relations (e.g., lack of trust) arising from inadequate decision making could adversely affect the overall efficiency in supply networks. Hence, in the remaining sections of this manuscript, and more explicitly in conducting the case study, we adopt a more general view of behavioural issues in corporate bond networks, addressing how the "quality of relations" between supply network members can enhance efficiency.

DEA and network DEA in banking industry

Since Charnes et al. (1978) introduced data envelopment analysis (DEA), numerous studies have used DEA, either singly or in combination with mathematical and/or statistical models, to measure relative efficiency of decision making units (DMUs) (Emrouznejad, Parker, & Tavares, 2008). DEA has been widely applied to measure efficiency in certain tiers or in the overall processes of supply chains (Liang, Yang, Cook, & Zhu, 2006b; Yang, Wu, Liang, Bi, & Wu, 2011). However, conventional DEA models do not consider the internal processes of DMUs; rather, they treat the system as a "black box". The network DEA model (Fare & Grosskopf, 2000), an alternative to the black box model, enables managers to identify sources of inefficiencies in different stages of a network (Kao, 2014b; Kao & Hwang, 2008, 2010). Network DEA has been applied extensively, from the banking industry (e.g., Akther et al., 2013; Lozano, 2015; Matthews, 2013) to other industrial and services sectors (Mirhedayatian et al., 2014; Moreno & Lozano, 2014; Vaz, Camanho, & Guimarães, 2010). Several recent studies have applied network DEA to the banking industry, measuring the efficiency of commercial banks: Akther et al. (2013) evaluated the efficiency of 21 commercial banks in Bangladesh in a two-staged network using the slacks-based inefficiency measure; Matthews (2013) developed a three-stage network slacks-based DEA framework that incorporated risk measures (i.e., financial and human resources-related risks) and non-profit loans to evaluate the efficiency of 15 domestic and commercial banks and four foreign banks in China; and Wang, Huang, Wu, and Liu (2014) adopted an additive two-stage DEA with non-profit loans as undesirable outputs to measure the efficiency of 16 main Chinese commercial banks, identifying several factors that improve efficiency in this sector.

Despite focusing on commercial banking, our study differs from the above in several ways. First, we did not limit the inputs and outputs of the corporate bond network model to merely tangible financial criteria; rather, we included the behavioural issues that might arise in this network, indicated by the "quality of relations" between each of the members in this network. Second, we considered only those processes related to issuing and underwriting bonds (excluding loans and deposits) by commercial banks. In this way we adopted a holistic view that incorporates all the players (i.e., issuer, underwriter, bank, and investors) within the corporate bond network as one single DMU.

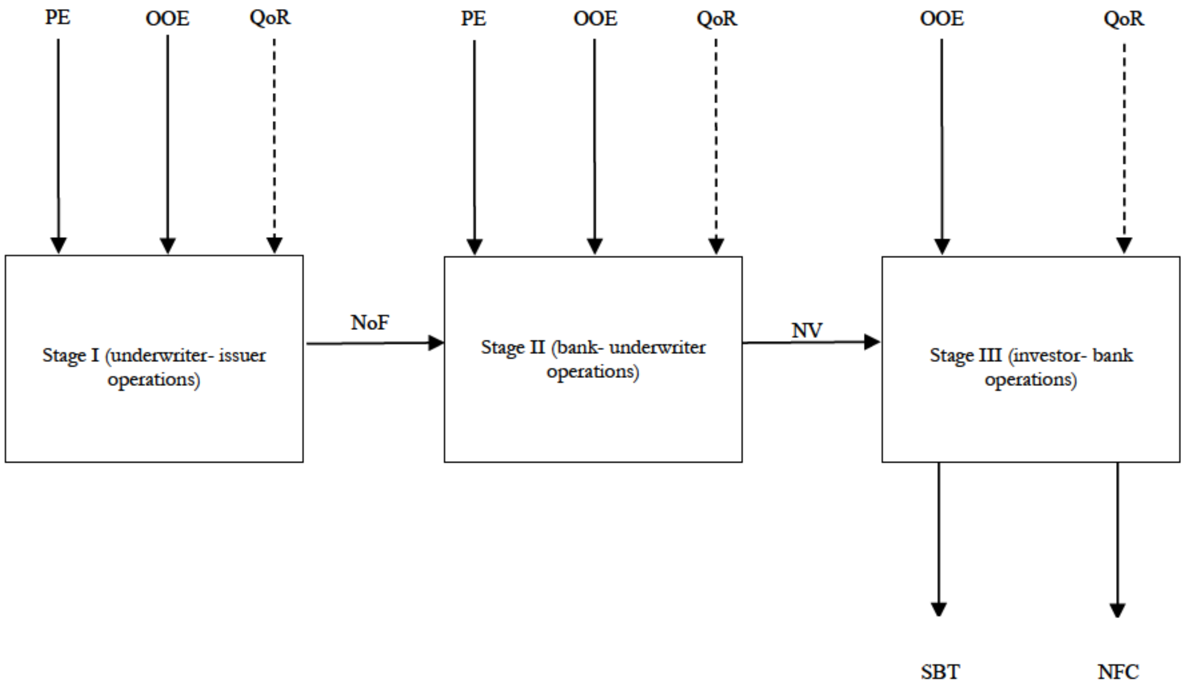
Methodology

We adopted a multi-method approach using both quantitative and qualitative research methods to capture operational and decision making-related inefficiencies in the corporate bond network. Multi-method approaches apply multiple methodologies from the same or different disciplines and are ideal for studying a phenomenon and understanding its complexities (Boyer & Swink, 2008; Sanders & Wagner, 2011). Indeed, the increased rigor and reliability of adopting multi-method approaches results in "greater insights into research problems, reduction in the myopic, disciplined-based perspective, and greater potential for innovative SCM [Supply Chain Management] breakthroughs" (Sanders and Wagner (2011, p. 318), p. 318. Similarly, combining several research methodologies such as survey, archival, behavioural, and case studies allows a deeper understanding of the phenomenon and increases the practical contributions of the research (Fawcett & Waller, 2011). In this section, we first use DEA modelling as a quantitative method to model all operational and behavioural factors that could affect efficiency in the corporate bond network. We then discuss the case, further describing the semi-structured interview and critical incident technique used to gather in-depth information about the underlying behavioural factors affecting the quality of relations within this network.

Network DEA model of the corporate bond network

Figure 3.1 presents the three stages in the corporate bond network and their associated inputs, outputs, and intermediary inputs/outputs. We aimed to measure technical efficiency instead of cost or allocative efficiency of the corporate bond network. To this end, we adopted the frequently used "intermediation approach" to assign interest expenses and non-interest expenses as inputs, and interest income and non-interest income as outputs (for more information see, Fethi & Pasiouras, 2010). Given the dynamics of the corporate bond network and the exclusion of interest incomes (i.e., loans and deposits), we defined several non-interest expenses and non-interest incomes in the three stages of the corporate bond network as inputs and outputs.

Figure 3.1 Corporate bond network



Legend: PE (personnel expenses), OOE (other operational expenses), QoR (quality of relations), NoF (number of referrals), NV (net value of issued bonds), SBT (proportion of sold bonds to total), NFC (net fees and commissions)

As shown in Figure 3.1, personnel expenses (PE) (x_{11},x_{21}) and various other operational expenses (OOE) (x_{21}, x_{22}) are used separately by the bank and underwriter in both Stage I and Stage II to yield referrals for bond underwriting and issuance (NoF) (z_1) and to issue bonds (NV) (z_2). Other operational expenses for marketing and selling bonds (OOE) (x_{31}) in Stage III are inputs to produce final non-interest incomes of the network, including proportion of bonds sold to total bonds (SBT) (y_{31}) and net fees and commissions (NFC) (y_{32}). Depending on the quality of relations between network members, hidden costs of deteriorating relations and lack of trust in the network might also be considered, although these are not traditionally captured as a form of non-interest expenses. We therefore added the quality of bilateral relations (QoR) between underwriter-issuer ($\tilde{x}_{13}$), bank-underwriter ($\tilde{x}_{23}$), and bank-investors ($\tilde{x}_{32}$) as the additional inputs to the three stages in Figure 3.1, illustrated by dotted lines. Since there are no financial records or tangible measures to assess these behavioural inputs, and there are varying levels of uncertainties associated with them when evaluated by decision makers, we applied fuzzy sets theory to include quality of bilateral relations in our network DEA model. The "∼" sign in the figure shows that the variables representing QoR in three stages of the corporate bond network are associated with some level of uncertainty.

Following Kao (2009) and Fare, Grosskopf, Lovell, and Pasurka (1989), the overall efficiency of the corporate bond network (Figure 3.1) for DMU_k using the network DEA is formulated in model (1):

$$E_k = Max \frac{u_{31}y_{31}^k + u_{32}y_{32}^k}{\sum_{i=1}^{2}(v_{1i}x_{1i}^k + v_{2i}x_{2i}^k) + v_{13}\tilde{x}_{13}^k + v_{23}\tilde{x}_{23}^k + v_{31}x_{31}^k + v_{32}\tilde{x}_{32}^k}$$

$$s.t. \begin{cases} \dfrac{u_{31}y_{31}^j + u_{21}y_{32}^j}{\sum_{i=1}^{2}\left(v_{1i}x_{1i}^j + v_{2i}x_{2i}^j\right) + v_{13}\tilde{x}_{13}^j + v_{23}\tilde{x}_{23}^j + v_{31}x_{31}^j + v_{32}\tilde{x}_{32}^j} \leq 1 \\ \dfrac{w_1 z_1^j}{\sum_{i=1}^{2}\left(v_{1i}x_{1i}^j\right) + v_{13}\tilde{x}_{13}^j} \leq 1 \\ \dfrac{w_2 z_2^j}{\sum_{i=1}^{2}\left(v_{2i}x_{2i}^j\right) + v_{23}\tilde{x}_{23}^j + w_1 z_1^j} \leq 1 \\ \dfrac{u_{31}y_{31}^j + u_{32}y_{32}^j}{v_{31}x_{31}^j + v_{32}\tilde{x}_{32}^j + w_2 z_2^j} \leq 1 \\ j = 1,2,\dots,n \\ u_{31}, u_{32} \geq 0 \\ v_{11}, v_{12}, v_{13}, v_{21}, v_{22}, v_{23}, v_{31}, v_{32} \geq 0 \\ w_1, w_2 \geq 0 \end{cases} \tag{1}$$

where $x_{hi}^j, i = 1,2,3$ denotes the ith input, $y_{hr}^j, r = 1,2$ the rth output, and $z_f^j, f = 1,2$ of the fth intermediary input/output of jth DMU, $j = 1, \dots n$ for the hth sub-process, $h = 1,2,3$. The linear equivalent of model (1) (Charnes & Cooper, 1962) is presented in model (2):

$$E_k = Max\ u_{31}y_{31}^k + u_{32}y_{32}^k \tag{2}$$

$$
s.t.\begin{cases}
\sum_{i=1}^{2}(v_{1i}x_{1i}^{k}+v_{2i}x_{2i}^{k})+v_{13}\tilde{x}_{13}^{k}+v_{23}\tilde{x}_{23}^{k}+v_{31}x_{31}^{k}+v_{32}\tilde{x}_{32}^{k}=1\\
u_{31}y_{31}^{j}+u_{21}y_{32}^{j}-(\sum_{i=1}^{2}(v_{1i}x_{1i}^{j}+v_{2i}x_{2i}^{j})+v_{13}\tilde{x}_{13}^{j}+v_{23}\tilde{x}_{23}^{j}+v_{31}x_{31}^{j}+v_{32}\tilde{x}_{32}^{j})\le 0\\
w_{1}z_{1}^{j}-(\sum_{i=1}^{2}(v_{1i}x_{1i}^{j})+v_{13}\tilde{x}_{13}^{j})\le 0\\
w_{2}z_{2}^{j}-(\sum_{i=1}^{2}(v_{2i}x_{2i}^{j})+v_{23}\tilde{x}_{23}^{j}+w_{1}z_{1}^{j})\le 0\\
u_{31}y_{31}^{j}+u_{32}y_{32}^{j}-(v_{31}x_{31}^{j}+v_{32}\tilde{x}_{32}^{j}+w_{2}z_{2}^{j})\le 0\\
j=1,2,\dots,n\\
u_{31},u_{32}\ge 0\\
v_{11},v_{12},v_{13},v_{21},v_{22},v_{23},v_{31},v_{32}\ge 0\\
w_{1},w_{2}\ge 0
\end{cases}
$$

Once the optimal values of multipliers $u_{31}^{*}, u_{32}^{*}, v_{11}^{*}, v_{12}^{*}, \dots, v_{32}^{*}$, and w_{1}^{*}, w_{2}^{*} are obtained using model (2), the overall network efficiency and efficiency of sub-processes are calculated using equations (3a–3d):

$$
E_k=\frac{u_{31}^{*}y_{31}^{k}+u_{32}^{*}y_{32}^{k}}{\sum_{i=1}^{2}(v_{1i}^{*}x_{1i}^{k}+v_{2i}^{*}x_{2i}^{k})+v_{13}^{*}\tilde{x}_{13}^{k}+v_{23}^{*}\tilde{x}_{23}^{k}+v_{31}^{*}x_{31}^{k}+v_{32}^{*}\tilde{x}_{32}^{k}} \tag{3a}
$$

$$
E_k^{1}=\frac{w_{1}^{*}z_{1}^{k}}{\sum_{i=1}^{2}(v_{1i}^{*}x_{1i}^{k})+v_{13}^{*}\tilde{x}_{13}^{k}} \tag{3b}
$$

$$
E_k^{2}=\frac{w_{2}^{*}z_{2}^{k}}{\sum_{i=1}^{2}(v_{2i}^{*}x_{2i}^{k})+v_{23}^{*}\tilde{x}_{23}^{k}+w_{1}^{*}z_{1}^{k}} \tag{3c}
$$

$$
E_k^{3}=\frac{u_{31}^{*}y_{31}^{k}+u_{32}^{*}y_{32}^{k}}{v_{31}^{*}x_{31}^{k}+v_{32}^{*}\tilde{x}_{32}^{k}+w_{2}^{*}z_{2}^{k}} \tag{3d}
$$

Application of fuzzy sets theory to the three-stage Network DEA model

Given that QoR inputs (i.e., $\tilde{x}_{13}$, $\tilde{x}_{23}$, $\tilde{x}_{32}$) in the proposed model (see Figure 3.1) are uncertain and are related to the behavioural traits of decision makers, they are evaluated by linguistic variables. Sample selection and data gathering procedures are discussed in detail in subsequent sections. Linguistic variables, however, are associated with a certain measure of ambiguity (Zadeh, 1975); in the case of the corporate bond network this is reflected within the expert valuations of the identified behavioural factors. Thus, fuzzy sets theory (Bellman & Zadeh, 1970; Zadeh, 1965) was applied to quantify these variables.

Using the α-cut method, we computed the upper and lower limits of the α-cuts of the system efficiency according to the model proposed by Kao and Liu (2011). Subsequently, we obtained the bounds of each process, considering the limits of system efficiency. This paper uses triangular fuzzy numbers (TFN) to quantify linguistic evaluations of experts on behavioural factors. TFNs are widely used due to their simplicity and solid theoretical basis (Pedrycz, 1994). A TFN can be shown as a triple (a_1, a_2, a_3), where a_1, a_2, and a_3 are real numbers and $a_1 \leq a_2 \leq a_3$. The membership function of (a_1, a_2, a_3):

$$\begin{cases} 0, & x \leq a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \leq x \leq a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \leq x \leq a_3 \\ 0, & x \geq a_3 \end{cases} \tag{4}$$

Using (4), the fuzzy variables (i.e., $\tilde{x}_{13}$, $\tilde{x}_{23}$, $\tilde{x}_{32}$) are specified in the form of fuzzy numbers in (5a)–(5c). Therefore, model (2) becomes a fuzzy DEA model. As Hatami-Marbini et al. (2011) argued in their taxonomy of fuzzy DEA, the class of α-level approaches is the most popular fuzzy DEA model. In this paper, we apply a similar model based on *a*-level sets to solve the fuzzy network DEA model (2). An *a*-level set is a crisp set of objects with its membership degree in fuzzy set being greater than or equal to *a*. For a TFN (a_1, a_2, a_3), its *a*-level set at a given value of *a* could be specified by a closed interval of $[a_\alpha^L, a_\alpha^U] = [(1 - \alpha)a_1 + \alpha a_2, \alpha a_2 + (1 - \alpha)a_3]$. Consequently, fuzzy variables (i.e., $\tilde{x}_{13}$, $\tilde{x}_{23}$, $\tilde{x}_{32}$) in model (2) are rearranged as TFNs $(x_{13}^1, x_{13}^2, x_{13}^3)$, $(x_{23}^1, x_{23}^2, x_{23}^3)$, $(x_{32}^1, x_{32}^2, x_{32}^3)$. The corresponding *a*-level of this set of TFNs for a specific value of *a* is as follows:

$$[(x_{13})_\alpha^L, (x_{13})_\alpha^U] = [(1-\alpha)x_{13}^1 + \alpha x_{13}^2, \alpha x_{13}^2 + (1-\alpha)x_{13}^3] \quad (5a)$$

$$[(x_{23})_\alpha^L, (x_{23})_\alpha^U] = [(1-\alpha)x_{23}^1 + \alpha x_{23}^2, \alpha x_{23}^2 + (1-\alpha)x_{23}^3] \quad (5b)$$

$$[(x_{32})_\alpha^L, (x_{32})_\alpha^U] = [(1-\alpha)x_{32}^1 + \alpha x_{32}^2, \alpha x_{32}^2 + (1-\alpha)x_{32}^3] \quad (5c)$$

Considering (5a)–(5c), the upper bound efficiency of DMU_k at a specific α-level is determined by solving the following:

$$(E_k)_\alpha^U = Max\ u_{31}y_{31}^k + u_{32}y_{32}^k$$

$$s.t.\begin{cases}
\sum_{i=1}^{2}\left(v_{1i}x_{1i}^k + v_{2i}x_{2i}^k\right) + v_{13}\left(x_{13}^k\right)_\alpha^L + v_{23}\left(x_{23}^k\right)_\alpha^L + v_{31}x_{31}^k + v_{32}\left(x_{32}^k\right)_\alpha^L = 1 \\
u_{31}y_{31}^k + u_{21}y_{32}^k - \left(\sum_{i=1}^{2}\left(v_{1i}x_{1i}^k + v_{2i}x_{2i}^k\right) + v_{13}\left(x_{13}^k\right)_\alpha^L + v_{23}\left(x_{23}^k\right)_\alpha^L + v_{31}x_{31}^k + v_{32}\left(x_{32}^k\right)_\alpha^L\right) \le 0 \\
u_{31}y_{31}^j + u_{21}y_{32}^j - \left(\sum_{i=1}^{2}\left(v_{1i}x_{1i}^j + v_{2i}x_{2i}^j\right) + v_{13}\left(x_{13}^j\right)_\alpha^U + v_{23}\left(x_{23}^j\right)_\alpha^U + v_{31}x_{31}^j + v_{32}\left(x_{32}^j\right)_\alpha^U\right) \le 0, j \ne \\
w_1z_1^k - \left(\sum_{i=1}^{2}\left(v_{1i}x_{1i}^k\right) + v_{13}\left(x_{13}^k\right)_\alpha^L\right) \le 0 \\
w_1z_1^j - \left(\sum_{i=1}^{2}\left(v_{1i}x_{1i}^j\right) + v_{13}\left(x_{13}^j\right)_\alpha^U\right) \le 0, j \ne k \\
w_2z_2^k - \left(\sum_{i=1}^{2}\left(v_{2i}x_{2i}^k\right) + v_{23}\left(x_{23}^k\right)_\alpha^L + w_1z_1^k\right) \le 0 \\
w_2z_2^j - \left(\sum_{i=1}^{2}\left(v_{2i}x_{2i}^j\right) + v_{23}\left(x_{23}^j\right)_\alpha^U + w_1z_1^j\right) \le 0, j \ne k \\
u_{31}y_{31}^k + u_{32}y_{32}^k - \left(v_{31}x_{31}^k + v_{32}\left(x_{32}^k\right)_\alpha^L + w_2z_2^k\right) \le 0 \\
u_{31}y_{31}^j + u_{32}y_{32}^j - \left(v_{31}x_{31}^j + v_{32}\left(x_{32}^k\right)_\alpha^U + w_2z_2^j\right) \le 0 \\
j = 1,2,\dots,n \\
u_{31}, u_{32} \ge 0 \\
v_{11}, v_{12}, v_{13}, v_{21}, v_{22}, v_{23}, v_{31}, v_{32} \ge 0 \\
w_1, w_2 \ge 0
\end{cases}$$

Similar to model (2), and after calculating optimal values for $u_{31}^*, u_{32}^*, v_{11}^*, v_{12}^*, \dots, v_{32}^*$, and w_1^*, w_2^*, the upper bound overall α-cut efficiency score of the network and efficiency of its sub-processes for DMU_k are obtained using the following equations (7a)–(7d):

$$(E_k)_\alpha^U = \frac{u_{31}^* y_{31}^k + u_{32}^* y_{32}^k}{\sum_{i=1}^{2}(v_{1i}^* x_{1i}^k + v_{2i}^* x_{2i}^k) + v_{13}^* \left(x_{13}^k\right)_\alpha^L + v_{23}^* \left(x_{23}^k\right)_\alpha^L + v_{31}^* x_{31}^k + v_{32}^* \left(x_{32}^k\right)_\alpha^L} \tag{7a}$$

$$(E_k^1)_\alpha^U = \frac{w_1^* z_1^k}{\sum_{i=1}^{2}\left(v_{1i}^* x_{1i}^k\right) + v_{13}^* \left(x_{13}^k\right)_\alpha^L} \tag{7b}$$

$$(E_k^2)_\alpha^U = \frac{w_2^* z_2^k}{\sum_{i=1}^{2}\left(v_{2i}^* x_{2i}^k\right) + v_{23}^* \left(x_{23}^k\right)_\alpha^L + w_1^* z_1^k} \tag{7c}$$

$$(E_k^3)_\alpha^U = \frac{u_{31}^* y_{31}^k + u_{32}^* y_{32}^k}{v_{31}^* x_{31}^k + v_{32}^* \left(x_{23}^k\right)_\alpha^L + w_2^* z_2^k} \tag{7d}$$

The upper bound model presented in model (6) is obtained by setting fuzzy input variables for DMU_k at their lower bounds, while other DMUs take the upper bound values of these variables. Kao and Liu (2011) and Kao and Liu (2014) show that the lower bound efficiency of the overall network and its sub-processes is calculated using the dual model of (2). According to the duality theorem (Dantzig, 1963), the objective functions of the primal and dual models of the network in Figure 3.1 yield the same value. Using the dual of model (2), the lower bound efficiency of the overall network at a certain α-level for DMU_k is as below:

$$(E_0)_\alpha^L = Min\ \varepsilon((\sum_{i=1}^{2} s_{1i}^v) + s_{13}^v + (\sum_{i=1}^{2} s_{2i}^v) + s_{23}^v + s_{31}^v + s_{32}^v + s_1^w + s_2^w + s_{31}^u + s_{32}^u) \tag{8}$$

$$
s.t.\begin{cases}
\theta x_{1i}^{k} - \sum_{j=1}^{n} \alpha_j x_{1i}^{j} - \sum_{j=1}^{n} \beta_j x_{1i}^{j} - s_{1i}^{v} = 0, i = 1,2 \\
\theta\left(x_{13}^{k}\right)_{\alpha}^{U} - \left[\alpha_k\left(x_{13}^{k}\right)_{\alpha}^{U} - \sum_{j=1,j\neq k}^{n} \alpha_j\left(x_{13}^{j}\right)_{\alpha}^{L}\right] - \left[\beta_k\left(x_{13}^{k}\right)_{\alpha}^{U} - \sum_{j=1,j\neq k}^{n} \beta_j\left(x_{13}^{j}\right)_{\alpha}^{L}\right] - s_{13}^{v} = 0 \\
\theta x_{2i}^{k} - \sum_{j=1}^{n} \alpha_j x_{2i}^{j} - \sum_{j=1}^{n} \beta_j x_{2i}^{j} - s_{2i}^{v} = 0, i = 1,2 \\
\theta\left(x_{23}^{k}\right)_{\alpha}^{U} - \left[\alpha_k\left(x_{23}^{k}\right)_{\alpha}^{U} - \sum_{j=1,j\neq k}^{n} \alpha_j\left(x_{23}^{j}\right)_{\alpha}^{L}\right] - \left[\beta_k\left(x_{23}^{k}\right)_{\alpha}^{U} - \sum_{j=1,j\neq k}^{n} \beta_j\left(x_{23}^{j}\right)_{\alpha}^{L}\right] - s_{23}^{v} = 0 \\
\theta x_{31}^{k} - \sum_{j=1}^{n} \alpha_j x_{31}^{j} - \sum_{j=1}^{n} \beta_j x_{31}^{j} - s_{31}^{v} = 0, i = 1,2 \\
\theta\left(x_{32}^{k}\right)_{\alpha}^{U} - \left[\alpha_k\left(x_{32}^{k}\right)_{\alpha}^{U} - \sum_{j=1,j\neq k}^{n} \alpha_j\left(x_{32}^{j}\right)_{\alpha}^{L}\right] - \left[\beta_k\left(x_{32}^{k}\right)_{\alpha}^{U} - \sum_{j=1,j\neq k}^{n} \beta_j\left(x_{32}^{j}\right)_{\alpha}^{L}\right] - s_{32}^{v} = 0 \\
\sum_{j=1}^{n} \beta_j z_1^{j} - \sum_{j=1}^{n} \gamma_j z_1^{j} - s_1^{w} = 0 \\
\sum_{j=1}^{n} \gamma_j z_2^{j} - \sum_{j=1}^{n} \delta_j z_2^{j} - s_2^{w} = 0 \\
\sum_{j=1}^{n} \alpha_j y_{31}^{j} - \sum_{j=1}^{n} \gamma_j y_{31}^{j} - s_{31}^{u} = y_{31}^{k} \\
\sum_{j=1}^{n} \alpha_j y_{32}^{j} - \sum_{j=1}^{n} \gamma_j y_{32}^{j} - s_{32}^{u} = y_{32}^{k} \\
\alpha_j, \beta_j, \gamma_j, \delta_j, s_{1i}^{v}, s_{13}^{v}, s_{2i}^{v}, s_{23}^{v}, s_{31}^{v}, s_{32}^{v}, s_1^{w}, s_2^{w}, s_{31}^{u}, s_{32}^{u} \geq 0 \\
i = 1,2 \\
j = 1,2,\ldots,n
\end{cases}
$$

Once the optimal values $s_{31}^{u*}, s_{32}^{u*}, s_{11}^{v*}, s_{12}^{v*}, \ldots, s_1^{w*}, s_2^{w*}$ are determined and replaced by $u_{31}^{*}, u_{32}^{*}, v_{11}^{*}, v_{12}^{*}, \ldots, w_1^{*}, w_2^{*}$, the lower bound overall α-cut efficiency score of the network and efficiency of its sub-processes for DMU_k are obtained using the following equations (9a)–(9d):

$$
(E_k)_{\alpha}^{L} = \frac{u_{31}^{*} y_{31}^{k} + u_{32}^{*} y_{32}^{k}}{\sum_{i=1}^{2}(v_{1i}^{*} x_{1i}^{k} + v_{2i}^{*} x_{2i}^{k}) + v_{13}^{*}\left(x_{13}^{k}\right)_{\alpha}^{U} + v_{23}^{*}\left(x_{23}^{k}\right)_{\alpha}^{U} + v_{31}^{*} x_{31}^{k} + v_{32}^{*}\left(x_{32}^{k}\right)_{\alpha}^{U}} \tag{9a}
$$

$$(E_k^1)_\alpha^L = \frac{w_1^* z_1^k}{\sum_{i=1}^{2}\left(v_{1i}^* x_{1i}^k\right) + v_{13}^*\left(x_{13}^k\right)_\alpha^U} \tag{9b}$$

$$(E_k^2)_\alpha^L = \frac{w_2^* z_2^k}{\sum_{i=1}^{2}\left(v_{2i}^* x_{2i}^k\right) + v_{23}^*\left(x_{23}^k\right)_\alpha^U + w_1^* z_1^k} \tag{9c}$$

$$(E_k^3)_\alpha^L = \frac{u_{31}^* y_{31}^k + u_{32}^* y_{32}^k}{v_{31}^* x_{31}^k + v_{32}^*\left(x_{23}^k\right)_\alpha^U + w_2^* z_2^k} \tag{9d}$$

To obtain the fuzzy efficiency of DMU_k, the lower bound and upper bound efficiency models are solved for $\alpha = 0$ and $\alpha = 1$. The triangular fuzzy efficiency of DMU_k is determined as $\widetilde{E_0} = \left[(E_0)_0^L, (E_0)_1, (E_0)_0^U\right]$ considering $(E_0)_1 = (E_0)_1^L = (E_0)_1^U$ (see Table 3.2). The values of $\widetilde{E_j}, j = 1,2,\dots,n$ are the triangular fuzzy efficiencies that will be used to meet the model's objectives. The above-mentioned α-level-based approach could be extended to different membership functions by using their corresponding α-levels in the lower-bound and upper-bound models.

Case example

We investigated corporate bond networks in Iran, including several commercial banks, their corporate banks, external investment banks, their corporate clients, and investors. Iran's emerging market, its significant potential for investments, and simultaneous lack of sufficient scientific analyses of its economic and financial environment for the past 36 years have made it an intriguing area of exploration by foreign investors (Wright & Thornton, 2015). Additionally, the fixed 20% coupon on investments in the corporate and government bonds has raised global interest in Iran's bond market (Ramezanpour, 2015; Rao, 2014a). Since its inauguration in the 1990s and following the same global standards, issuing and underwriting bonds in Iran has created an annual turnover of millions and in some cases billions of US dollars (Ramezanpour, 2015). Government and corporate bonds were previously issued by independent investment banks, but after corporate banking was introduced into Iran's financial market in 2007, both investment banks and corporate banks have been competing to gain a larger share of the corporate bond market. According to our model in Figure 3.1, each DMU consists of a specific commercial bank, its corporate bank or an investment bank (underwriter), a corporate client (issuer), and investors who purchase the bonds. Including four commercial banks (Eghtesad Novin (EN) Bank, Mellat Bank, Melli Bank, and Saman Bank), their corporate banking divisions and four investment banks (Amin, Novin, Omid, Sepehr) resulted in 20 corporate bond networks as independent DMUs (see Table 3.2). In all these DMUs, members have collaborated with each other in at least one relevant bond issuing and underwriting project. The names of corporate clients and investors are not included here because of the banks' confidentiality policies.

Data collection and application

Following the guidelines of Yin (2009), we examined relevant archival data of nominated banks and investment banks and official auditing reports issued by the commercial banks and Central Bank of Iran to obtain the required data for non-fuzzy inputs, outputs, and intermediary inputs/outputs (see Figure 3.1). Descriptive statistics of the input and output data are available upon request. Following the suggestions by Fawcett et al. (2011), we then conducted semi-structured interviews with representatives from banks, investment banks, corporate clients, and investors, in order to determine the values for fuzzy inputs (i.e., quality of relations between members of the corporate bond network) within the model.

We used Critical Incident Technique (CIT) during the interviews to gain a better insight into the underlying behavioural factors that adversely affect efficiency in corporate bond network. CIT is defined as "a qualitative interview procedure, which facilitates the investigation of significant occurrences (events, incidents, processes, or issues) identified by the respondent, the way they are managed, and the outcomes in terms of perceived effects" (Chell, 1998, p. 56). The application of CIT to analyse human behaviour, especially in service contexts such as the banking industry, has several benefits (Gremler, 2004):

i. it provides a rich source of data by guiding respondents toward giving a range of responses based on first-hand experiences and through storytelling (Gabbott & Hogg, 1996),
ii. it represents what respondents actually think, thus avoiding any preconceptions or hasty judgments about how respondents perceive incidents to be important (Chell, 1998; Stauss, 1993),
iii. it provides rich and concrete information that is applicable by managers and decision makers to improve real-world practices (Stauss, 1993).

In addition to the above, CIT is an inductive method and so is most helpful when little is known about the topic under investigation (Gremler, 2004), such as the study of behavioural factors affecting efficiency in the corporate bond network.

We conducted 22 interviews with representatives from banks, investment banks, corporate customers, and investors between December 2013 and March 2014. The interviews were conducted to the point where redundancies were occurring and no new sets of incidents were achieved (Flanagan, 1954). Respondent profiles and a sample of interview protocols are presented in Appendix 2 and Appendix 3, respectively.

Interviewing time ranged between 30 minutes and two hours. Multiple investigators conducted the interviews and analysed the outcomes to ensure validity of the results (Benbasat, Goldstein, & Mead, 1987a; Eisenhardt, 1989). Sampling process followed the theoretical sampling principles of Glaser and Strauss (1967), whereby the relationships between concepts and dimensions are revealed in the first few interviews. The sample comprised mostly middle/top managers of the banks, corporate banks, investment banks, and the corporate clients as the main decision makers of their organization, along with groups of individual customers. The interview protocol was initially developed by the authors and was reviewed by three researchers familiar with qualitative research and behavioural sciences. The semi-structured interview protocol using CIT (Flanagan, 1954) allowed for open discussions unconstrained by preconceptions, which made it adjustable to the respondents' feedback (Gioia, Corley, & Hamilton, 2013).

The interview protocol consisted of four main parts (Appendix 2). Part (A) comprised general questions about interviewees' responsibilities that were relevant to the processes in the corporate bond network. Additionally, respondents were asked to remember their negative experiences dealing with other members of the corporate bond network and the likely behavioural factors behind them. Based on respondents' experiences, in Part (B) we asked them to analyse and prioritize the impact of those experiences on the quality of relations with the other member(s) with whom they were directly interacting, and the likelihood of respondents continuing to work with those members in the future. In parts (C) and (D) we asked respondents if they knew about any possible links relevant to the quality of relations between other members of the network and their impact on their negative experiences in the network.

Data interpretation

Data analysis incorporated both content analytic method (Kassarjian, 1977) and an interpretive approach (Holbrook & O'Shaughnessy, 1988). Because the sample was small, transcripts were analysed manually, with two co-authors carrying out the coding. Critical incidents were chosen from the content, based on relevance to the topic of study. Considering we were interested in the main behavioural factors that could affect efficiency at each stage in the corporate bond network, we reported on all identified behavioural factors relevant to bond issuing, underwriting, and selling processes as critical incidents, ordered by frequency of mention by respondents. Inter-rater reliability of 86% was based on the number of agreed coding decisions to the total number of decisions (Kassarjian, 1977). Any disagreements about the coding were resolved between the co-authors before reporting the results. The most important critical incidents for each stage according to their frequency (above 10%) are reported in Table 3.1. We also adopted an interpretive approach (Holbrook & O'Shaughnessy, 1988), delineating the possible causes of the behavioural factors identified, since "employing an interpretive approach may help researchers better understand emotions in the context of the critical incidents" (Gremler, 2004, p. 79). Thus, borrowing from the literature on behavioural operations and supply chain management as well as how respondents felt about different situations categorized as critical incidents, we also reported on the possible causes of the main behavioural factors in Table 3.1. We interpreted possible causes of the incidents as either independent or linked to other incidents identified in the interviews (Edvardsson & Strandvik, 2000). For instance, "mistrust", mentioned by most respondents as the overriding behavioural factor affecting the quality of relations in all three stages, could stem from either anchoring on past negative experiences, as interpreted by the authors, or it could result from the opportunistic behaviour by the services supplier (i.e., investment bank, corporate bank, or bank), as mentioned by respondents. The interpretations of the critical incidents by the authors were examined by four colleagues who were experts in behavioural sciences or service supply chains.

In addition to the behavioural factors discussed in the literature review section above, Table 3.1 includes other behavioural regularities believed to cause inefficiencies in corporate bond service networks. For instance, "overestimating financial stability of issuer" in Stage I is interpreted to be due to "information avoidance" of bank decision makers, which prevents them making unbiased judgments of their corporate customers' financial stability. Information avoidance is the tendency to overlook information that causes discomfort and, in the context of supply chain management, it could result in several biased decisions by managers regarding their suppliers, customers, or investments in different projects (Gino & Pisano, 2008a). Other authors provide a description of the behavioural factors, their causes mentioned in Table 3.1, and their application in the context of operations and supply chain management (Bendoly et al., 2010; Gino & Pisano, 2008a). Other possible causes of this overestimation could be banks' "overconfidence" in their accurate evaluation of issuers' financial stability, or continuing to work with financially unstable issuers based merely on the costs already incurred and which cannot be recovered without considering future losses (i.e., "sunk costs fallacy"). Knowing details of the behavioural factors could contribute to more effective post hoc analyses of the sources of inefficiencies obtained from the DEA model. We further elaborate on this later in the results and discussion section.

Table 3.1 Behavioural factors affecting quality of relations in the corporate bond network in three stages

Stage I (underwriter-issuer operations)			Stage II (bank-underwriter operations)			Stage III (investor-bank operations)		
Behavioural factor	**Frequency**	**Possible cause**	**Behavioural factor**	**Frequency**	**Possible cause**	**Behavioural factor**	**Frequency**	**Possible cause**
Mistrust	38%	Anchoring of issuer Opportunistic behaviour by underwriter	Mistrust	46%	Anchoring of bank Opportunistic behaviour by underwriter	Mistrust	42%	Anchoring of investor Opportunistic behaviour by bank
Unethical and unprofessional behaviour by the issuer	19%	Lack of motivation, feedback and control on underwriter's employees	Banks favouring existing corporate customers over obtaining new customers	10%	Loss aversion of bank decision makers	Unethical and unprofessional behaviour by the bank	22%	Lack of motivation, feedback and control on bank's employees
Overestimating financial stability of issuer (default risk)	12%	Overconfidence of bank decision makers Information avoidance of bank decision makers Sunk costs fallacy of bank decision makers	Opportunistic behaviour of the issuer	10%	Illusion of control by banks decision makers and lack of sufficient supervisory mechanisms	Investors' unwillingness to purchase the bonds	16%	Conservatism of investors Risk aversion of investors Mistrust

Once respondents had identified all the behavioural factors, they were asked to prioritize the quality of their relations with other members in the corporate bond network. Linguistic terms were used in the form of five-point Likert scale, with each scale being transformed into a TFN (i.e., "very low" (1,1,3), "low"(1,3,5), "neutral" (3,5,7), "high" (5,7,9), and "very high" (7,9,9)). The average scores obtained by the interviews specific to each stage for each DMU were used in the proposed fuzzy network DEA model. For instance, if investors evaluated quality of their relations with Mellat Bank's officers high on average and they had not noticed much misbehaviours the TFN (5,7,9) was replaced as the value of $\tilde{x}_{32}$ for all the corporate bonds with Mellat Bank in them. The DMUs presented in Table 3.2, despite having some similarities, differ in having either investment banks or corporate banks as their underwriters, and this distinction is made in Table 3.2 by reporting the efficiency scores of those DMUs separately.

Table 3.2 illustrates the numerical outcomes of the study using the proposed fuzzy network DEA model, presenting the overall efficiency scores and the efficiency scores in each of the three stages. On average, corporate bond networks with corporate banks as their underwriters showed marginally better overall efficiency. However, comparison of stage-wise efficiency scores reveal that corporate bond networks with investment banks as underwriters were performing significantly better in Stage I ($p - value = 0.00$), indicating to more efficienct underwriter-issuer operations in this network. Nevertheless, in Stage II corporate bank-bank operations showed higher levels of efficiency compared to investment bank-bank operations ($p - value = 0.01$). No significant difference is observed in performance of the two networks in Stage III.

Table 3.2 Efficiency scores of the corporate bond underwriting and issuance network

DMU	Overall efficiency score ($\tilde{E}_j$)	Overall rank	Stage I efficiency score ($\tilde{E}_j^1$)	Stage II efficiency score ($\tilde{E}_j^2$)	Stage III efficiency score ($\tilde{E}_j^3$)
DMUs with corporate banks as underwriters					
EN[a] Bank- EN Corporate Bank	(0.94, 0.95, 0.99)	8	(0.18, 0.19, 0.35)	(0.9, 0.9, 0.96)	(1, 1, 1)
Mellat Bank - Mellat Corporate Bank	(0.94, 0.97, 1)	4	(0.26, 0.26, 0.27)	(0.98, 0.98, 1)	(0.95, 0.97, 1)
Melli Bank- Melli Corporate Bank	(0.96, 1, 1)	2	(0.23, 0.39, 0.49)	(0.97, 1, 1)	(0.98, 1, 1)
Saman Bank - Saman Corporate Bank	(0.95, 0.98, 1)	3	(0.23, 0.23, 0.40)	(1, 1, 1)	(0.95, 0.98, 1)
Mean	(0.95, 0.98, 1)		(0.23, 0.27, 0.38)	(0.96, 0.97, 0.99)	(0.97, 0.99, 1)
Number of efficient DMUs	0		0	1	1
DMUs with investment banks as underwriters					
EN Bank- Amin Investment Bank	(0.80, 0.80, 0.93)	12	(0.25, 0.25, 1)	(0.75, 0.75, 0.89)	(1, 1, 1)
EN Bank- Novin Investment Bank	(1, 1, 1)	1	(0.54, 0.63, 0.63)	(0.84, 0.9, 1)	(1, 1, 1)
EN Bank- Omid Investment Bank	(0.83, 0.92, 1)	9	(0.83, 0.83, 1)	(0.94, 0.94, 1)	(0.88, 0.92, 1)
EN Bank- Sepehr Investment Bank	(0.89, 1, 1)	7	(0.68, 0.68, 1)	(0.95, 0.95, 1)	(0.93, 1, 1)
Mellat Bank - Amin Investment Bank	(0.91, 0.99, 1)	5	(0.93, 1, 1)	(1, 1, 1)	(0.91, 0.99, 1)
Mellat Bank - Novin Investment Bank	(0.9, 1, 1)	6	(0.78, 0.78, 1)	(0.91, 0.91, 0.96)	(0.97, 1, 1)
Mellat Bank - Omid Investment Bank	(0.67, 0.68, 0.71)	20	(0.85, 0.85, 1)	(0.61, 0.61, 0.61)	(1, 1, 1)
Mellat Bank - Sepehr Investment Bank	(0.69, 0.72, 1)	17	(0.97, 0.98, 1)	(0.67, 0.67, 1)	(0.93, 0.99, 1)
Melli Bank - Amin Investment Bank	(0.72, 0.76, 1)	15	(0.85, 0.86, 1)	(0.70, 0.70, 1)	(0.95, 1, 1)
Melli Bank - Novin Investment Bank	(0.70, 0.74, 1)	16	(1, 1, 1)	(0.68, 0.68, 1)	(0.94, 0.99, 1)
Melli Bank - Omid Investment Bank	(0.59, 0.63, 1)	19	(1, 1, 1)	(0.62, 0.63, 1)	(0.84, 0.89, 1)

DMU	Overall efficiency score ($\tilde{E}_j$)	Overall rank	Stage I efficiency score ($\tilde{E}_j^1$)	Stage II efficiency score ($\tilde{E}_j^2$)	Stage III efficiency score ($\tilde{E}_j^3$)
Melli Bank - Sepehr Investment Bank	(0.78, 0.79, 0.81)	18	(0.80, 0.80, 1)	(0.78, 0.78, 0.78)	(.097, 0.97, 1)
Saman Bank - Amin Investment Bank	(0.78, 0.80, 1)	11	(0.82, 0.82, 0.91)	(0.77, 0.77, 0.78)	(1, 1, 1)
Saman Bank - Novin Investment Bank	(0.80, 0.83, 1)	10	(0.82, 0.82, 0.93)	(0.83, 0.83, 1)	(0.96, 0.97, 1)
Saman Bank - Omid Investment Bank	(0.74, 0.77, 1)	13	(0.87, 0.87, 1)	(0.75, 0.75, 0.75)	(0.94, 0.98, 1)
Saman Bank - Sepehr Investment Bank	(0.74, 0.77, 1)	13	(0.84, 0.84, 1)	(0.76, 0.76, 1)	(0.97, 0.97, 1)
Mean	(0.78, 0.83, 0.97)		(0.80, 0.81, 0.97)	(0.79, 0.79, 0.92)	(0.89, 0.98, 1)
Number of efficient DMUs	1		2	1	4
Mann-Whitney U (Prob > X2, one-tailed)	13.50 (0.08)		2.00 (0.00) [b]	6.50 (0.01) [b]	30.00 (0.89)
Wilcoxon W (Prob > X2, one-tailed)	149.50 (0.08)		12.00 (0.00) [b]	142.50 (0.01) [b]	166.00 (0.89)

[a] *Eghtesad Novin*

[b] *Significant at 0.01 level*

Individual rankings of the DMUs showed that while most of the corporate bond networks showed higher overall efficiency scores with corporate banks as underwriters, Eghtesad Novin Bank was more efficient when collaborating with investment banks, rather than its own corporate bank, for bond issuance and underwriting. In fact, the corporate bond network of Eghtesad Novin- Novin Investment Bank has the highest efficiency score among all other DMUs. Another observation from Table 3.2 and Figure 3.3 is a surprisingly lower efficiency in issuer-corporate bank operations compared to other stages in these networks. This could have serious implications for banks to increase supervision and control over how corporate banks are dealing with corporate customers for bond underwriting and issuance purposes. We delve deeper into the specific sources of inefficiencies for all networks in the next section.

Results and discussion

Figures 3.2 and 3.3 illustrate the comparisons between efficiency scores in different stages for the corporate bond network with investment banks or corporate banks as underwriters. In both figures, the efficiency level of the network in Stage III is higher than in the other two stages. However, the patterns of overall efficiency scores and Stage II efficiency scores are most similar. This could be an indicator that the performance of bank and underwriter in Stage II is determinant of the overall efficiency of the corporate bond network. Thus, this could be interpreted as banks paying specific attention to bank-underwriter operations in the corporate bonds network to ensure an acceptable overall efficiency in this network.

In order to determine with more certainty which sets of inputs or outputs in the corporate bond network model have the highest levels of impact on the overall efficiency, we conducted several tests of sensitivity and a robustness check of the efficiency scores to variations in inputs and outputs.

Figure 3.2 Comparison of efficiency scores at $\alpha = 1$ for corporate bond network with investment banks as underwriters

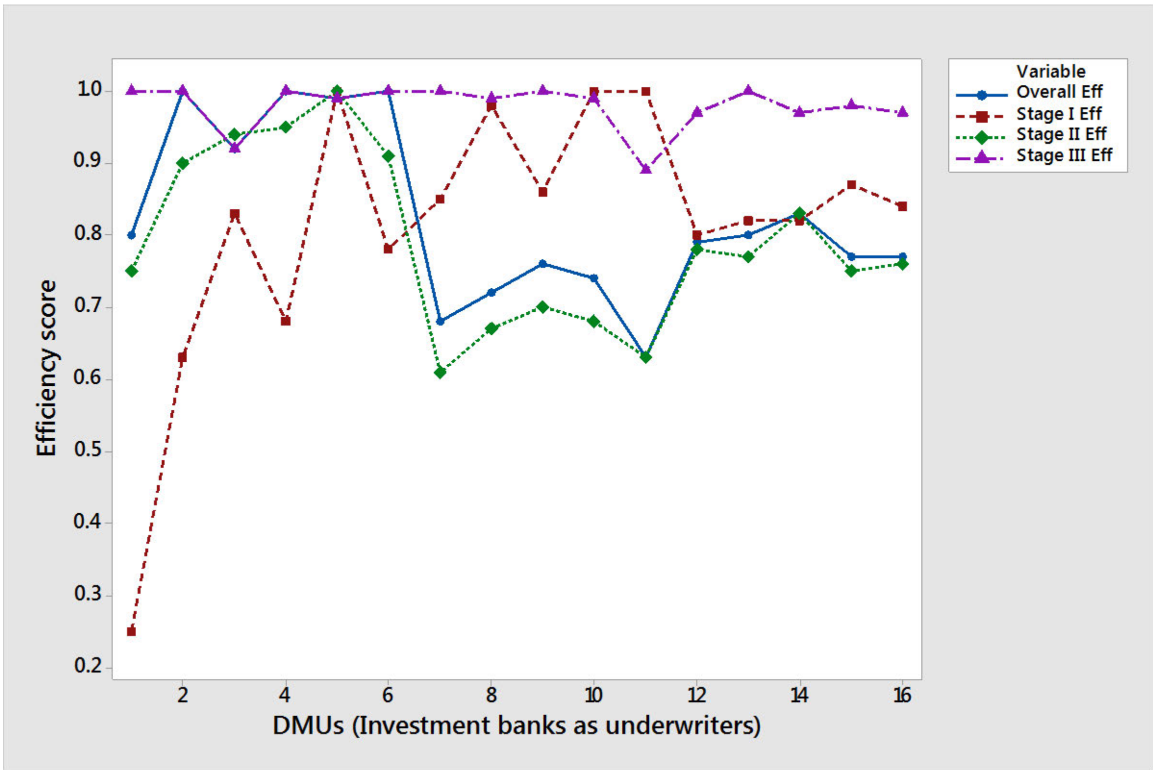
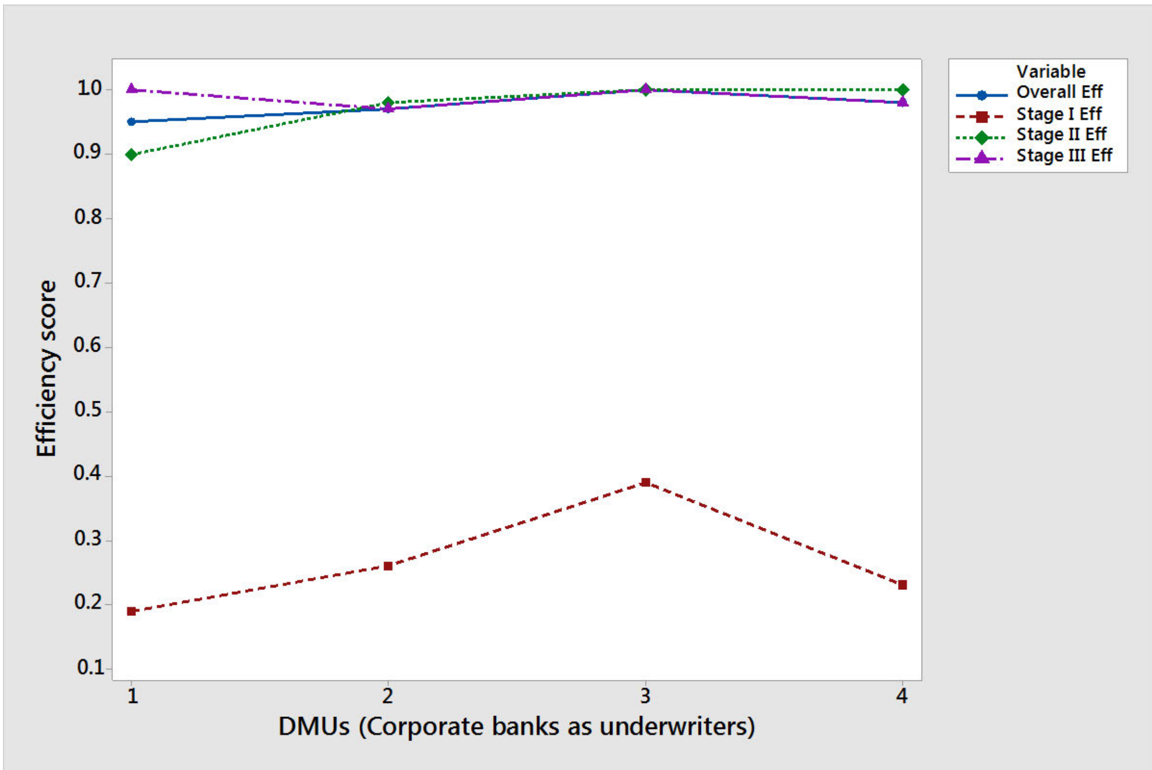


Figure 3.3 Comparison of efficiency scores at $\alpha = 1$ for corporate bond network with corporate banks as underwriters



Initially, we tested the sensitivity of the results to the sample size. Overall, the model in Figure 3.1 had twelve inputs, outputs, and intermediary inputs/outputs. As a general heuristic, this requires at least 36 (12*3) DMUs to ensure an acceptable level of discrimination. Kao (2009), however, explains that in network DEA models the total number of DMUs are multiplied by the number of sub-processes. Considering the total number of 20 DMUs and three sub-processes (20*3>12*3), we are confident that our sample size was sufficient. Table 3.3 illustrates potential improvements in efficiency scores by making changes in the inputs and outputs of the corporate bond network model, compared with the benchmark frontier. The results are reported using the full sample and two subsamples that represent networks with either corporate banks or investment banks as their underwriters.

Table 3.3 Forecast changes in inputs and outputs against the benchmark frontier (%)

Stage I (underwriter-issuer operations)				
	Excess PE[c]	Excess OOE	Excess QoR	
Full sample	0.00	–1.30	**–8.69**	
Subsample 1[a]	0.00	–0.76	**–10.62**	
Subsample 2[b]	0.00	0.00	**–3.64**	
Stage II (bank-underwriter operations)				
	Excess PE[d]	Excess OOE	Excess QoR	
Full sample	–0.44	0.00	**–3.41**	
Subsample 1	0.00	0.00	**–2.47**	
Subsample 2	–0.85	0.00	**–6.63**	
Stage III (investor-bank operations)				
	Excess PE	Excess QoR	Shortage SBT[e]	Shortage NFC
Full sample	–1.22	–1.22	**–3.66**	**2.55**
Subsample 1	–1.38	–1.38	**–3.42**	**6.54**
Subsample 2	–1.37	–1.37	**–2.00**	**6.43**

[a] *Sample with corporate banks as underwriters*
[b] *Sample with investment banks as underwriters*
[c] *Excess indicates to percentage decrease in inputs and shortage indicates increase to outputs against efficient frontier. Bold numbers illustrate the largest changes projected.*
[d] *PE (personnel expenses), OOE (other operational expenses), QoR (quality of relations)*
[e] *SBT (proportion of sold bonds to total), NFC (net fees and commissions)*

As shown in Table 3.3, most inefficiencies in the first two stages stem mainly from "quality of relations" (QoR) between either underwriter and issuer or bank and underwriter. Further investigation of sources of inefficiencies for QoR revealed that, while in Stage I corporate banks show a poorer quality of relations with issuers, in Stage II investment banks' relations with banks has more potential for improvement. Considering a significantly lower level of efficiency in Stage I for the networks with corporate banks as their underwriters (see Figure 3.3), Table 3.3 reveals that the overriding priority for improvement in these networks should be improving the relations between banks and their own corporate banking divisions. Additionally, in

Stage III most of the inefficiencies are embedded in QoR and also "proportion of bonds sold to total" (SBT), which calls for the banks' decision makers to pay attention to their relations with their investors, gaining their trust, and using alternative marketing strategies to sell the bonds.

Managerial implications

The results of this study reveal that managers should pay equal attention to operational and behavioural factors when addressing inefficiencies within supply networks. The sources of inefficiencies in the corporate bond network identified in Table 3.2 indicate that the quality of bilateral relations should be improved in all three stages. As discussed earlier, we posited several reasons for the poor quality of relations depicted in the three stages of corporate bond networks. Taking this into consideration, we recommend that managers take the following steps to help overcome inefficiencies caused by behavioural issues throughout their supply network.

First, for instance in Stage I, having identified and acknowledged goals by the employees regarding the quality of services they offer to the issuer, managers should implement a control and feedback mechanism to constantly monitor individuals' motivation levels, thereby keeping employees of investment banks or corporate banks motivated enough to provide quality services to issuers. Second, managers should apply control mechanisms and supervision over issuers (especially the investment bank) to preclude them adopting opportunistic behaviour. The latter should also be addressed by strengthening trust levels between bank and issuer. Third, managers should implement debiasing strategies to reduce the impact of identified behavioural biases (e.g., anchoring, overconfidence, suck costs fallacy) on the quality of decisions made in Stage I by providing warnings and awareness about the decision biases, decomposing complex decision tasks into smaller components, and applying multiple perspectives to view decision tasks (Kaufmann, Michel, & Carter, 2009; Tokar, Aloysius, & Waller, 2012).

Other debiasing measures to be taken in supply chains can reduce the effects of dynamism in the decision-making context (Haines, Hough, & Haines, 2010; Kaufmann et al., 2009). Overall, the extent of dynamism in the environment moderates between rational and comprehensive decision making and decision quality (Hough & White, 2003). Reducing dynamism in Stage I and in the corporate bond network in general requires identifying changes in business and updating marketing strategies for the bonds, and applying tools and mechanisms that could detect and address changes in both external and internal operational and behavioural factors affecting efficiency in this network. Furthermore, an unambiguous set of information could help reduce complexities in the decision-making environment, leading to fewer biases in the decision-making process (Kaufmann et al., 2009). This could be achieved in the corporate bond network by developing databases that could capture and analyse all information relevant to the operational and behavioural factors identified in this study. In fact, gathering information more frequently and efficiently, especially in dynamic environments such as supply networks, is believed to be critical to engage decision makers in "procedural rationality" as an important decision-making approach (Haines et al., 2010; Riedl, Kaufmann, Zimmermann, & Perols, 2013).

In Stage II, quality of relations between underwriters and banks was identified as the primary source of inefficiency in the corporate bond network (Table 3.2). The deteriorating relations in this stage could have adverse consequences on Stage I in terms of opportunistic behaviour of the underwriter, as discussed above. To avoid this outcome, the same measures and debiasing strategies discussed for Stage I should be adopted. Additionally, in Stage III, both operational and behavioural factors had significant negative effects on the stage-wise and overall efficiency of the network (Table 3.2). First, the proportion of bonds sold in relation to the total quantity of bonds is contingent upon several behavioural and non-behavioural factors. The non-behavioural factors are usually context-specific and depend upon the return on investment promised by parallel markets (in case of Iran's market, the real estate industry for instance offers much higher returns on investment than the bonds market) or the quality of bonds and marketing strategies for the bonds to attract investors. Similarly, the overriding behavioural factors affecting investors' decisions to purchase the bonds include, for example, trust between investors and bank and the reputation of corporate customer and bank as issuer and seller of the bonds. Thus, managers should consider that operational inefficiencies identified in the supply networks could stem equally from behavioural and operational factors, or perhaps even more from behavioural factors in some cases.

Conclusion

This study attempted to highlight the role of behavioural factors in analytical models used in the operations and supply chain management domain. By adopting a multi-method approach, we incorporated behavioural misconducts of decision makers in standard DEA models for measuring bank efficiency, and we gathered relevant data on behavioural factors using semi-structured interviews and critical incident technique. We developed a fuzzy network DEA model to reveal the sources of inefficiencies in issuer-underwriter, underwriter-bank, and bank-investor interrelations in the presence of behavioural factors in this network. The results showed marginal differences in the efficiency of the networks with either investment banks or corporate banks as their underwriters. Conducting sensitivity analysis on the inputs and outputs of the model in three stages revealed that behavioural factors in corporate bond networks could significantly affect efficiency scores in the network.

While we envisioned mainly decision making-related scenarios that could be disrupted by decision makers' bounded rationality, the results from the case analysis showed additional behavioural issues present in the bilateral relations throughout the corporate bond network. From this aspect, a limitation of this study framework was that it adopted a general approach toward all the behavioural issues identified in the DEA modelling of the network. Analysing specific behavioural factors in supply networks would provide more in-depth knowledge of the root causes of errors in judgment and decision making, although such analyses would be limited in number because of the over-complexity of the behavioural models. A second limitation is that we utilized semi-structured interviews and critical incident techniques to gain insight into the behavioural misconducts within the banking industry, despite some authors arguing that laboratory experiments are preferable (Knemeyer & Naylor, 2011) because they control for irrelevant biases that might cause errors in the final results of the analyses.

We recommend that researchers consider incorporating behavioural factors into their performance and efficiency assessment models of supply networks, in order to improve the application of these models to real-world problems. Moreover, the outcomes of this study suggest that decision makers should be more aware of intangible variables, including those behavioural factors in their interrelations with their counterparts in supply networks in general and in the corporate bond service networks in particular.

3.3. Paper 5-6: Risk preferences and ordering decisions in supply chains[6]

Inventory decisions in multi-echelon supply chains can be affected by both operational and behavioural factors. Much research has investigated the role of operational inefficiencies on oscillations and variations in order quantities of supply chain echelons, but the study of behavioural factors, including risk attitudes that affect ordering decisions in supply chains is still nascent. In this paper, we examine the attitudes of decision makers toward risk and their impact on the ordering decisions in multi-echelon supply chains. In particular, we investigate whether risk aversion/risk seeking, loss aversion or prospect theory could predict the ordering decisions made in supply chains. We develop analytical models to predict order quantities in supply chains with revenue and cost parameters, as well as supply chains with only cost aspects, as in a classical beer distribution game. Using controlled laboratory experiments, we verify if the models predict the ordering behaviour of supply chain members. We find that only risk-aversion and risk-seeking models can partially predict the empirical results of the experiment. We also find that participants with higher scores in statistical numeracy and risk literacy tests demonstrate a significantly better performance in the beer game. Overall, our findings show that participants over-order when making profits and under-order when incurring losses in supply chain.

Key words behavioural operations; risk; loss aversion; prospect theory; bullwhip effect; laboratory experiment

[6] Pournader, M., Narayanan, C., & Keblis M. (2016). *Prospect Theory and Ordering Behavior in Multi-echelon Supply Chains*. MSOM Conference, Auckland, New Zealand, Jun. 2016 (Oral presentation).

Pournader, M., Narayanan, A., & Keblis M. Risk Attitudes and Ordering Behavior in Multi-echelon Supply Chains, Apr. 2016 (Working paper).

Note: The original version was presented at MSOM Conference (June 2016). The version included in this thesis is the revised version as a working paper for journal submission.

Introduction

One of the most well known phenomena in supply chains is the order oscillation and amplification and therefore inventory swings from downstream to upstream supply chain tiers, known as the "bullwhip effect" (Lee, 1997). The bullwhip effect could result in many undesiarable consequences, such as excessive investment on inventory, transportation disruption, lost revenues and periodic stockouts, among others. Only recently the slow economic growth in China caused demand volatilities causing excessive costs in global supply chains (Sheffi, 2015).

It has been argued that the bullwhip effect could be the result of both operational and behavioural causes. Some operational sources that cause bullwhip effect are price variation, order batching, demand signal processing and rationing game caused by shortages (Lee, 1997). In addition to these operational causes, some solutions – such as everyday low pricing, using third party logistics, vendor managed inventory and information sharing – can also mitigate the bullwhip effect (Lee, 1997; Lee et al., 2004). These operational solutions, along with training, are shown to be insufficient to completely eliminate the bullwhip effect (e.g., Tokar et al., 2012; Wu & Katok, 2006), and therefore the behavioural causes of the bullwhip effect should be taken into account (Croson et al., 2014).

Some scholars have attempted to link the bullwhip effect to a variety of behavioural anomalies (e.g., Croson & Donohue, 2006; Croson et al., 2014; Narayanan & Moritz, 2015; Sterman, 1989b), aiming to address human cognitive limitations and their effect on inventory decisions, and hence the bullwhip effect. Nevertheless, no published studies have examined risk preferences of supply chain decision makers and their attitudes toward uncertainty. The importance of such investigation relies in the context in which global supply chains are embedded and the day-to-day uncertainties they confront. By considering so many market and operational factors and the uncertainties associated with them, supply chain managers should be able to minimize costs by making the best decisions about their ordering quantities and inventory levels.

This study aims to contribute to the latter by investigating decision makers' attitudes toward risks and their impact on their ordering decisions. In doing so we initially provide a review of the most relevant and recent studies that have focused on the behavioural causes of the bullwhip effect in supply chains. Considering that we extract the risk aversion/risk seeking and loss aversion models from the value functions of the prospect theory (PT), we also discuss the few studies in the literature that have investigated PT in inventory decisions, and specifically in the newsvendor settings. We then construct the analytical models that predict ordering behaviours according to the aforementioned behavioural models toward risk. Our models consider two different types of beer game: the traditional beer game with only cost parameters, and the beer game with the addition of a revenue parameter to correspond more with real-world supply chain practices. Next we compare the empirical results from conducting the beer game with the proposed models and investigate compatibilities between the two. The final section presents the conclusions and implications for future research.

Background

The bullwhip effect

The bullwhip effect in supply chains refers to increased order oscillation and variation from downstream to upstream supply chain members, culminating in adverse consequences such as increased costs of inventory or backorders. Studies show the bullwhip effect is omnipresent in a variety of industries (Lee, 1997; Lee et al., 2004; Sterman, 2000). While the bullwhip effect and its countermeasures are well known, many companies still experience it (Bray & Mendelson, 2012; Duan, Yao, & Huo, 2015).

The study of behavioural causes of the bullwhip effect is an emerging field in which experimental studies are adopted to address how bounded rationality and limited levels of sophistication in reasoning could culminate in under- or over-estimating inventory decision parameters in supply chains (e.g., Croson & Donohue, 2003; Croson & Donohue, 2006; Sterman, 1989a, 1989b; Tokar et al., 2012; Wu & Katok, 2006). In a number of most recent studies, Croson et al. (2014) investigated the role of coordination risk as a possible behavioural cause of the bullwhip effect. Using a set of laboratory experiments, they found that, even when all the environmental and operational causes of the bullwhip effect are absent, coordination risk could be construed as a trigger of order oscillation and amplification in supply chains. Considering the presence of both operational and behavioural factors causing the bullwhip effect, (Croson et al., 2014) also provided several implications for performance improvement, such as the addition of coordination stock, establishing trust between supply chain decision makers and creating common knowledge. Narayanan and Moritz (2015) investigated how the cognitive profile of decision makers could in fact be an underlying cause for the bullwhip effect. They also found that, even when operational causes of the bullwhip effect are mitigated, participants with tendency to underweight the supply line showed lower levels of cognitive ability. Tokar, Aloysius, Waller, and Hawkins (2015) identified all the different forms of framing effect (Levin, Schneider, & Gaeth, 1998) in ordering behaviour of supply chain decision makers. They also found that the subjects of their experiments were inclined to hold less than optimum inventory, which they showed could be eliminated by framing the same ordering decision in terms of losses. This implies the role of loss aversion in tuning the ordering quantity.

In spite of efforts to study different aspects of the behavioural causes of bullwhip effect, the literature calls for more research that could shed a light on behavioural roots of ordering decisions in multi-echelon supply chains (Croson et al., 2014; Tokar et al., 2012; Wan & Evers, 2011), more specifically through the lens of risk attitudes and risk preferences of supply chain decision makers (Narayanan & Moritz, 2015).

Risk preferences and prospect theory

This paper draws on the principles of (cumulative) prospect theory (PT) by Kahneman and Tversky (1979) to examine if PT can predict ordering decisions in multi-echelon supply chains. PT is perceived to be one of the main theories explaining decision making under risk that explain the deviations from expected utility theory such as framing effects, Alliax paradox and the certainty effect (Kahneman & Tversky, 1979). PT has four main elements: reference dependence, loss aversion, diminishing sensitivity and probability weighting. First, losses and gains in PT are compared to a reference point to derive utility. Thus, instead of absolute magnitudes of attributes of interest unlike expected utility theory, changes in those attributes are considered in PT, known as reference dependence. Second, decision makers are more sensitive to losses than to gains of equal nominal value, referred to as loss aversion. Third, diminishing sensitivity indicates that sensitivity toward changes closer to the reference point is higher than changes further away from the reference point. Moreover, the value function of PT is concave for gains and convex for losses, showing risk-aversion and risk-seeking behaviour in gain and loss domains, respectively. Finally, according to probability weighing of PT, people weigh outcomes not by their objective probability but instead by using their transformed weight of the probability.

One of the prominent studies of PT in operations and supply chain management is that by Schweitzer and Cachon (2000), which evaluated PT as an explanation of ordering decisions in the newsvendor inventory control setting. The authors studied both high-profit and low-profit newsvendor settings in two demand scenarios. Their experiments were set in a way that decision makers experienced only gains in one scenario and both losses and gains in another. They found that PT predicts the results only when both gains and losses are possible. More specifically, when the prospects are only gains they rule out PT as a predictor of ordering behaviours. In another more recent study, Nagarajan and Shechter (2014) reconfirmed past findings by incorporating probability weights of prospects in the newsvendor model using a continuous form of the cumulative PT. Similar to the study by Schweitzer and Cachon (2000), their findings contradict PT predictions of ordering patterns, compared with optimum order quantity. However, unlike the general understanding that PT is incapable of explaining ordering behaviour in inventory control environments, Long and Nasiry (2015) showed that, by changing the reference point from the zero payoff to the weighted average of highest and lowest possible payoffs, PT could in fact be used to explain ordering behaviour in a newsvendor environment. They used the idea of a stochastic reference point and a personal equilibrium framework (Kőszegi & Rabin, 2006) to form a new understanding of reference point that is beneficial in the adaptation of PT to newsvendor problem.

Model development

As part of the cumulative PT, Tversky and Kahneman (1992) proposed the following value function for w

$$v(w) = \begin{cases} w^{\alpha}, & w \geq w_0, \\ \lambda(w)^{\alpha}, & w < w_0, \end{cases} \tag{1}$$

where w is a unit of increase or decrease in the current amount of wealth (w_0) as the reference point, $\lambda > 0$ is a coefficient for loss aversion, and $\alpha > 0$ shows diminishing sensitivity to increasing amounts of losses and gains compared with w_0. The concavity in gains and convexity in losses as further properties of (1) applies to risk averse and risk seeking behaviour respectively. Based on experiments conducted by (Tversky & Kahneman, 1992), λ is estimated to be 2.25 and α to be 0.88. The literature (Booij, van Praag, & van de Kuilen, 2010) has reported on a range of values close to the original values proposed by Tversky and Kahneman (1992). For a perfectly rational decision maker, it follows that $\alpha = 1$ and $\lambda = 1$.

To investigate the predictions of PT for ordering decisions in supply chains we formulated losses in a traditional beer game for risk-averse/risk seeking ($\alpha < 1$) and loss-averse ($\lambda < 1$) decision makers and drew conclusions for ordering behaviour of subjects accordingly. We then considered both risk aversion/risk seeking and loss aversion, according to (1), in the value function of losses and investigated how the model predicts ordering behaviours considering the predictions of PT. We followed the same procedure for a beer game with an added revenue parameter (i.e., gain beer game) and we made predictions about ordering behaviour of subjects in the new setting.

Loss beer game: Risk-averse and risk-seeking preferences

Consider a supply chain member i (i.e., factory, distributor, wholesaler, retailer) in period t with a starting inventory of $I_{i,t}$, that receives a demand of $D_{i,t}$. The level of wealth of this supply chain member at the beginning of each period t is $w_{i,t}^{0}$. $w_{i,t}^{0}$ is the status quo level of wealth and a reference point at the beginning of the each period t of the game. Costs per unit of inventory and back orders are denoted by h and b, respectively. The change in the value of $w_{i,t}^{0}$ from one period to next is calculated as follows

$$w_{i,t} = \begin{cases} h\left(I_{i,t} - D_{i,t}\right), & I_{i,t} \geq D_{i,t}, w_{i,t} < w_{i,t}^{0}, \\ b\left(D_{i,t} - I_{i,t}\right), & I_{i,t} < D_{i,t}, w_{i,t} < w_{i,t}^{0}, \end{cases} \tag{2}$$

where $w_{i,t}$ shows the change in the $w_{i,t}^{0}$ for member i at the end of period t. Considering (1), the value function of losses for a risk-averse/risk seeking decision maker is

$$v(w_{i,t}) = \begin{cases} (h\left(I_{i,t} - D_{i,t}\right))^{\alpha}, & I_{i,t} \geq D_{i,t}, w_{i,t} < w_{i,t}^{0}, \\ (b\left(D_{i,t} - I_{i,t}\right))^{\alpha}, & I_{i,t} < D_{i,t}, w_{i,t} < w_{i,t}^{0}, \end{cases} \tag{3}$$

To further clarify the relationship between levels of inventory, demand quantity and ordering quantity, we used the following to denote the optimum order quantity $q_{i,t}$

$$q_{i,t} = D_{i,t+l} + S_i' - I_{i,t+l} - SL_{i,t+l}, \tag{4}$$

where $q_{i,t}$ represents the order placed by supply chain member i in period t, D is the demand, S' is a fixed value for a desired level of on-order and on-hand inventory for member i, I is the level of on-hand inventory including received shipment and backlog, and SL is the supply line of order inventory. The subscript l in (4) denotes the possible delay from ordering to receiving a certain amount of inventory. For instance, if the delay is four weeks ($l = 4$) and orders are placed on a weekly basis, the decision maker in week t should order considering the demand and inventory status in week $t + 4$.

By replacing $D_{i,t} - I_{i,t}$ from (3) with $q_{i,t} - S_i' + SL_{i,t+l}$ we can re-write (3) as

$$v(w) = \begin{cases} h^{\alpha}(S' - SL - q)^{\alpha}, & I \geq D, w < w_0, \\ b^{\alpha}(-S' + SL + q)^{\alpha}, & I < D, w < w_0, \end{cases} \tag{5}$$

where subscripts i, t, and l are omitted for brevity. Let $q^*(\alpha)$ denote the optimal order quantity predicted by (5) and q^* denote the optimum order quantity for a risk-neutral decision maker ($\alpha = 1$). We make the following proposition:

Proposition 1. Under the risk seeking and risk aversion conditions, when $I \geq D$ we have $q^*(\alpha) \geq q^*$, whereas when $I < D$ we have $q^*(\alpha) \leq q^*$.

Proof. Taking the partial derivative of (5) with respect to q gives

$$\frac{\partial}{\partial q} v(w) = \begin{cases} -\alpha h^{\alpha}(S' - SL - q)^{\alpha-1}, & I \geq D, w < w_0, \\ \alpha b^{\alpha}(-S' + SL + q)^{\alpha-1}, & I < D, w < w_0, \end{cases} \tag{6}$$

Next, taking the derivative of (6) with respect to α gives

$$\frac{\partial}{\partial \alpha}\left(\frac{\partial}{\partial q} v(w)\right) = \begin{cases} -h^{\alpha}(S' - SL - q)\,(1 + \alpha \ln h + \alpha \ln(S' - SL - q)), & I \geq D, w < w_0, \\ b^{\alpha}(-S' + SL + q)(1 + \alpha \ln b + \alpha \ln(-S' + SL + q)), & I < D, w < w_0, \end{cases} \tag{7}$$

It is easy to show that (7) is negative for $I \geq D$ and non-negative for $I < D$. Thus, for values of $0 \leq \alpha \leq 1$, it is concluded that $q^*(\alpha) \geq q^*$when $I \geq D$ and $q^*(\alpha) \leq q^*$ when $I < D$, supporting Proposition 1.

Loss beer game: Loss-aversion preferences

For a traditional loss beer game, the value function of a loss-averse decision maker according to (1) and (2) is

$$w = \begin{cases} \lambda h(I - D), & I \geq D, w < w_0, \\ \lambda b(D - I), & I < D, w < w_0, \end{cases} \tag{8}$$

Similar to the previous section ("*Loss beer game: Risk-averse and risk-seeking preferences*", page 133) and by replacing q from (4) in (8), it gives

$$v(w) = \begin{cases} \lambda h(S' - SL - q), & I \geq D, w < w_0, \\ \lambda b(-S' + SL + q), & I < D, w < w_0, \end{cases} \tag{9}$$

Let $q^*\ (\lambda)$ denote the optimal order quantity predicted by (9) for a loss-averse decision maker ($\lambda > 1$). Therefore we propose the following:

Proposition 2. Under the loss-aversion conditions, when $I \geq D$ we have $q^*\ (\lambda)\ \leq q^*$, whereas when $I < D$ we have $q^*\ (\lambda) \geq q^*$.

Proof. The partial derivative of (9) with respect to q is

$$\frac{\partial}{\partial q} v(w) = \begin{cases} -\lambda h, & I \geq D, w < w_0, \\ \lambda b, & I < D, w < w_0, \end{cases} \tag{10}$$

Next, taking the derivative of (10) with respect to λ gives

$$\frac{\partial}{\partial \lambda}\left(\frac{\partial}{\partial q} v(w)\right) = \begin{cases} -h, & I \geq D, w < w_0, \\ b, & I < D, w < w_0, \end{cases} \tag{11}$$

Clearly (11) is negative when $I \geq D$ and non-negative when $I < D$. Thus, for values of $\lambda \geq 1$, we have $q^*\ (\lambda) \leq q^*$ when $I \geq D$ and $q^*\ (\lambda) \geq q^*$ when $I < D$.

Loss beer game: Prospect theory preferences

From the findings in the previous two sections, it can be speculated that using risk aversion/risk seeking and loss aversion simultaneously in value function of the loss beer game might show contradictory results. Let $q^*_{PT}\ (\alpha, \lambda)$ denote the optimal order quantity predicted by PT. We propose the following:

Proposition 3. Under the PT conditions, no clear conclusion can be made about the relationship between $q^*_{PT}(\alpha, \lambda)$ and q^*.

Proof. It is clear that the value function of losses according to PT is

$$v(w) = \begin{cases} \lambda^\alpha h^\alpha (S' - SL - q)^\alpha, & I \geq D, w < w_0, \\ \lambda^\alpha b^\alpha (-S' + SL + q)^\alpha, & I < D, w < w_0, \end{cases} \tag{12}$$

By fixing an arbitrary $\lambda \geq 1$, we first investigated the changes in $q^*_{PT}(\alpha, \lambda)$ with respect to α. The partial derivative of (12) with respect to q gives

$$\frac{\partial}{\partial q} v(w) = \begin{cases} -\alpha\lambda^\alpha h^\alpha (S' - SL - q)^{\alpha-1}, & I \geq D, w < w_0, \\ \alpha\lambda^\alpha b^\alpha (-S' + SL + q)^{\alpha-1}, & I < D, w < w_0, \end{cases} \tag{13}$$

Next, taking the partial derivative of (13) with respect to α gives

$$\frac{\partial}{\partial \alpha}\left(\frac{\partial}{\partial q} v(w)\right) = \begin{cases} -\lambda^\alpha h^\alpha (S' - SL - q)(1 + \alpha \ln \lambda + \alpha \ln h + \alpha \ln(S' - SL - q)), & I \geq D, w < w_0, \\ \lambda^\alpha b^\alpha (-S' + SL + q)(1 + \alpha \ln \lambda + \alpha \ln b + \alpha \ln(-S' + SL + q)), & I < D, w < w_0, \end{cases} \tag{14}$$

From (14) it is easy to conclude for values of $0 \leq \alpha \leq 1$ and $I \geq D$ we have $q^*_{PT}(\alpha, \lambda) \geq q^*$ and for $I < D$ we have $q^*_{PT}(\alpha, \lambda) \leq q^*$. Next, we fix an arbitrary $0 < \alpha \leq 1$ and discuss the changes in $q^*_{PT}(\alpha, \lambda)$ with respect to λ. The partial derivative of (13) with respect to λ gives

$$\frac{\partial}{\partial\lambda}\left(\frac{\partial}{\partial q}v(w)\right)=\begin{cases}-\alpha^2\lambda^{\alpha-1}h^{\alpha}(S'-SL-q)^{\alpha-1}, & I\geq D, w<w_0,\\ \alpha^2\lambda^{\alpha-1}b^{\alpha}(-S'+SL+q)^{\alpha-1}, & I<D, w<w_0,\end{cases} \tag{15}$$

Looking at (15), for values of $\lambda \geq 1$, we have q^*_{PT} $(\alpha, \lambda) \leq q^*$ when $I \geq D$ and q^*_{PT} $(\alpha, \lambda) \geq q^*$ when $I < D$. The contradicting results for the partial derivatives of α and λ make it complicated to conclude about the ordering decisions according to PT when both loss-aversion and risk-aversion/risk-seeking behaviours are considered.

Gain beer game: Risk-averse and risk seeking preferences

Schweitzer and Cachon (2000) found PT could explain the results of their experiments when both loss and gain outcomes were possible. Moreover, developing analytical models and experiments that consider both gains and losses are more compatible with the real-world practices.

We therefore introduced a revenue parameter (r) for each unit of sales in the (gain) beer game. Thus, considering the same settings as in the earlier section entitled "*Loss beer game: Risk-averse and risk-seeking preferences*" on page 133, this time with the addition of r, losses and gains in multiple iterations of the beer game can be modelled as

$$w=\begin{cases} rD-h(I-D), & I\geq D, rD\geq h(I-D), w\geq w_0,\\ rI-b(D-I), & 0\leq I<D, rI\geq b(D-I), w\geq w_0,\\ h(I-D)-rD, & I\geq D, rD<h(I-D), w<w_0,\\ b(D-I)-rI, & 0\leq I<D, rI<b(D-I), w<w_0,\\ b(D-I), I<0, w<w_0, \end{cases} \tag{16}$$

Note that the first two cases of (16) correspond to conditions under which the decision maker will experience gains and the last three cases correspond to conditions under which the decision maker will experience losses.

For risk-averse and risk seeking preferences and considering (1), it gives

$$v(w)=\begin{cases}(rD-h(I-D))^{\alpha}, & I\geq D, rD\geq h(I-D), w\geq w_0,\\ (rI-b(D-I))^{\alpha}, & 0\leq I<D, rI\geq b(D-I), w\geq w_0,\\ (h(I-D)-rD)^{\alpha}, & I\geq D, rD<h(I-D), w<w_0,\\ (b(D-I)-rI)^{\alpha}, & 0\leq I<D, rI<b(D-I), w<w_0,\\ (b(D-I))^{\alpha}, I<0, w<w_0. & \end{cases} \tag{17}$$

Using (3) we replace $I-D$ and $D-I$ in (17) as follows

$$v(w)=\begin{cases}(rD-hS'+hSL+hq)^{\alpha}, & I\geq D, rD\geq h(I-D), w\geq w_0,\\ (rI+bS'-bSL-bq)^{\alpha}, & 0\leq I<D, rI\geq b(D-I), w\geq w_0,\\ (-rD+hS'-hSL-hq)^{\alpha}, & I\geq D, rD<h(I-D), w<w_0,\\ (-rI-bS'+bSL+bq)^{\alpha}, & 0\leq I<D, rI<b(D-I), w<w_0,\\ (-bS'+bSL+bq)^{\alpha}, I<0, w<w_0. & \end{cases} \tag{18}$$

Similar to 3.1., let $q^*(\alpha)$ denote the optimal order quantity predicted by (18) and q^* denote the optimum order quantity of a risk-neutral decision maker. We propose the following:

Proposition 4. Under the risk-seeking and risk-aversion conditions, when $I\geq D$ and $rD<h(I-D)$ holds and when $0\leq I<D$ and $rI\geq b(D-I)$ holds, we have $q^*(\alpha)\ \geq q^*$, whereas for all other conditions we have $q^*(\alpha)\ \leq q^*$.

Proof. Taking the partial derivative of (18) with respect to q gives

$$\frac{\partial}{\partial q}v(w)$$
$$=\begin{cases}\alpha h^{\alpha}(rD-hS'+hSL+hq)^{\alpha-1}, & I\geq D, rD\geq h(I-D), w\geq w_0,\\ -\alpha b^{\alpha}(rI+bS'-bSL-bq)^{\alpha-1}, & 0\leq I<D, rI\geq b(D-I), w\geq w_0,\\ -\alpha h^{\alpha}(-rD+hS'-hSL-hq)^{\alpha-1}, & I\geq D, rD<h(I-D), w<w_0,\\ \alpha b^{\alpha}(-rI-bS'+bSL+bq)^{\alpha-1}, & 0\leq I<D, rI<b(D-I), w<w_0,\\ \alpha b^{\alpha}(-bS'+bSL+bq)^{\alpha-1}, I<0, w<w_0, & \end{cases} \tag{19}$$

Next, taking the derivative of (19) with respect to α gives

$$\frac{\partial}{\partial \alpha}\left(\frac{\partial}{\partial q}v(w)\right)$$

$$= \begin{cases} h^{\alpha}(rD - hS' + hSL + hq)^{\alpha-1}(1 + \alpha \ln h + \alpha \ln(rD - hS' + hSL + hq)), & I \geq D, rD \geq h(I - D), w \geq w_0, \\ -b^{\alpha}(rI + bS' - bSL - bq)^{\alpha-1}(1 + \alpha \ln b + \alpha \ln(rI + bS' - bSL - bq)), & 0 \leq I < D, rI \geq b(D - I), w \geq w_0, \\ -h^{\alpha}(-rD + hS' - hSL - hq)^{\alpha-1}(1 + \alpha \ln h + \alpha \ln(-rD + hS' - hSL - hq)), & I \geq D, rD < h(I - D), w < w_0, \\ b^{\alpha}(-rI - bS' + bSL + bq)^{\alpha-1}(1 + \alpha \ln b + \alpha \ln(-rI - bS' + bSL + bq)), & 0 \leq I < D, rI < b(D - I), w < w_0, \\ b^{\alpha}(-bS' + bSL + bq)^{\alpha-1}(1 + \alpha \ln b + \alpha \ln(-bS' + bSL + bq)), I < 0, w < w_0, \end{cases} \quad (20)$$

It is easy to check (20) is negative when $I \geq D, rD < h(I - D)$ and $0 \leq I < D$, $rI \geq b(D - I)$ holds, culminating in $q^*(\alpha) \geq q^*$. For the remainder of the conditions in (20), $\frac{\partial}{\partial \alpha}\left(\frac{\partial}{\partial q}v(w)\right) \geq 0$ and therefore $q^*(\alpha) \leq q^*$.

Gain beer game: Loss-aversion preferences

The value function of losses for a loss-averse decision maker is

$$v(w) = \begin{cases} \lambda(-rD + hS' - hSL - hq), & I \geq D, rD < h(I - D), w < w_0, \\ \lambda(-rI - bS' + bSL + bq), & 0 \leq I < D, rI < b(D - I), w < w_0, \\ \lambda(-bS' + bSL + bq), I < 0, w < w_0, \end{cases} \quad (21)$$

Let $q^*\ (\lambda)$ denote the optimal order quantity predicted by (21) and q^* denote the optimum order quantity of a rational decision maker with $\lambda = 1$. We propose the following:

Proposition 5. Under the loss-aversion conditions, when $I \geq D$ we have $\lambda \leq q^*$, whereas when $I < D$ we have$\lambda \geq q^*$.

Proof. The partial derivative of (21) with respect to q is

$$\frac{\partial}{\partial q}v(w) = \begin{cases} -\lambda h, & I \geq D, rD < h(I - D), w < w_0, \\ \lambda b, 0 \leq I < D, rI < b(D - I), w < w_0, \\ \lambda b, I < 0, w < w_0, \end{cases} \quad (22)$$

Next, taking the derivative of (22) with respect to λ gives

$$\frac{\partial}{\partial\lambda}\left(\frac{\partial}{\partial q}v(w)\right) = \begin{cases} -h, \quad I \geq D, rD < h(I-D), w < w_0, \\ b, 0 \leq I < D, rI < b(D-I), w < w_0, \\ b, I < 0, w < w_0, \end{cases} \tag{23}$$

Clearly (23) is negative when $I \geq D$ and non-negative when $I < D$. Thus, for values of $\lambda \geq 1$, we have $q^*\ (\lambda) \leq q^*$ when $I \geq D$ and $q^*\ (\lambda) \geq q^*$ when $I < D$.

Gain beer game: Prospect theory preferences

The value function of PT for the gain beer game is

$$v(w) = \begin{cases} (rD - hS' + hSL + hq)^\alpha, \quad I \geq D, rD \geq h(I-D), w \geq w_0, \\ (rI + bS' - bSL - bq)^\alpha, \quad 0 \leq I < D, rI \geq b(D-I), w \geq w_0, \\ \lambda(-rD + hS' - hSL - hq)^\alpha, \quad I \geq D, rD < h(I-D), w < w_0, \\ \lambda(-rI - bS' + bSL + bq)^\alpha, \quad 0 \leq I < D, rI < b(D-I), w < w_0, \\ \lambda(-bS' + bSL + bq)^\alpha, I < 0, w < w_0. \end{cases} \tag{24}$$

Let $q_{PT}^*\ (\alpha, \lambda)$ denote the optimal order quantity predicted by (24) and q^* denote the optimum order quantity of a rational decision maker when $\alpha, \lambda = 1$. We propose the following:

Proposition 6. Under the prospect theory conditions, no clear conclusion can be made about the relationship between $q_{PT}^*(\alpha, \lambda)$ and q^*.

Proof. Similar to section "*Loss beer game: Prospect theory preferences*" on page 136, by fixing an arbitrary $\lambda \geq 1$, we first investigated the changes in $q_{PT}^*(\alpha, \lambda)$ with respect to α. Taking the partial derivative of (6) with respect to q gives

$$\frac{\partial}{\partial q}v(w) = \begin{cases} \alpha h^{\alpha}(rD - hS' + hSL + hq)^{\alpha-1}, \quad I \geq D, rD \geq h(I-D), w \geq w_0, \\ -\alpha b^{\alpha}(rI + bS' - bSL - bq)^{\alpha-1}, \quad 0 \leq I < D, rI \geq b(D-I), w \geq w_0, \\ -\alpha\lambda^{\alpha}h^{\alpha}(-rD + hS' - hSL - hq)^{\alpha-1}, \quad I \geq D, rD < h(I-D), w < w_0, \\ \alpha\lambda^{\alpha}b^{\alpha}(-rI - bS' + bSL + bq)^{\alpha-1}, \quad 0 \leq I < D, rI < b(D-I), w < w_0, \\ \alpha\lambda^{\alpha}b^{\alpha}(-bS' + bSL + bq)^{\alpha-1}, I < 0, w < w_0, \end{cases} \tag{25}$$

Next, taking the derivative of (7) with respect to α gives

$$\frac{\partial}{\partial \alpha}\left(\frac{\partial}{\partial q}v(w)\right)$$
$$= \begin{cases} h^{\alpha}(rD - hS' + hSL + hq)^{\alpha-1}(1 + \alpha\ln h + \alpha\ln(rD - hS' + hSL + hq)), \quad I \geq D, rD \geq h(I-D), w \geq w_0, \\ -b^{\alpha}(rI + bS' - bSL - bq)^{\alpha-1}(1 + \alpha\ln b + \alpha\ln(rI + bS' - bSL - bq)), \quad 0 \leq I < D, rI \geq b(D-I), w \geq w_0, \\ -\lambda^{\alpha}h^{\alpha}(-rD + hS' - hSL - hq)^{\alpha-1}(1 + \alpha\ln\lambda + \alpha\ln h + \alpha\ln(-rD + hS' - hSL - hq)), \quad I \geq D, rD < h(I-D), w < w_0, \\ \lambda^{\alpha}b^{\alpha}(-rI - bS' + bSL + bq)^{\alpha-1}(1 + \alpha\ln\lambda + \alpha\ln b + \alpha\ln(-rI - bS' + bSL + bq)), \quad 0 \leq I < D, rI < b(D-I), w < w_0, \\ \lambda^{\alpha}b^{\alpha}(-bS' + bSL + bq)^{\alpha-1}(1 + \alpha\ln\lambda + \alpha\ln b + \alpha\ln(-bS' + bSL + bq)), I < 0, w < w_0, \end{cases} \tag{26}$$

Next, we fixed an arbitrary $0 < \alpha \leq 1$ and discuss the changes in $q^*_{PT}(\alpha, \lambda)$ with respect to λ. We have

$$\frac{\partial}{\partial \lambda}\left(\frac{\partial}{\partial q}v(w)\right)$$
$$= \begin{cases} -\alpha^2\lambda^{\alpha-1}h^{\alpha}(-rD + hS' - hSL - hq)^{\alpha-1}, \quad I \geq D, rD < h(I-D), w < w_0, \\ \alpha^2\lambda^{\alpha-1}b^{\alpha}(-rI - bS' + bSL + bq)^{\alpha-1}, \quad 0 \leq I < D, rI < b(D-I), w < w_0, \\ \alpha^2\lambda^{\alpha-1}b^{\alpha}(-bS' + bSL + bq)^{\alpha-1}, I < 0, w < w_0. \end{cases} \tag{27}$$

From (26) and (27), when the outcomes are gains, we could derive the same conclusion for the risk aversion model in the earlier section entitled "*Gain beer game: Risk-averse and risk seeking preferences*" (page 137). However, when the outcomes are losses, and for values of $\alpha \leq 1$ and $\lambda \geq 1$, no consistent conclusion could be made about the relationship between $q^*_{PT}(\alpha, \lambda)$ and q^*.

Table 3.4 summarizes the results obtained from developing the models for risk preferences above.

Table 3.4 Summary of the propositions

	$w \geq w_0$		$w < w_0$		
	$I \geq D$	$0 \leq I < D$	$I \geq D$	$0 \leq I < D$	$I < 0$
Loss game					
Risk aversion and risk seeking	N/A	N/A	$q^*\,(\alpha) \geq q^*$	$q^*\,(\alpha) \leq q^*$	$q^*\,(\alpha) \leq q^*$
Loss-aversion	N/A	N/A	$q^*\,(\lambda) \leq q^*$	$q^*\,(\lambda) \geq q^*$	$q^*\,(\lambda) \geq q^*$
Prospect Theory	N/A	N/A	Inconclusive	Inconclusive	Inconclusive
Gain game					
Risk aversion and risk seeking	$q^*\,(\alpha) \leq q^*$	$q^*\,(\alpha) \geq q^*$	$q^*\,(\alpha) \geq q^*$	$q^*\,(\alpha) \leq q^*$	$q^*\,(\alpha) \leq q^*$
Loss-aversion	N/A	N/A	$q^*\,(\lambda) \leq q^*$	$q^*\,(\lambda) \geq q^*$	$q^*\,(\lambda) \geq q^*$
Prospect Theory	$q^*_{PT}\,(\alpha, \lambda) \leq q^*$	$q^*_{PT}\,(\alpha, \lambda) \geq q^*$	Inconclusive	Inconclusive	Inconclusive

Behavioural experiment

The beer distribution game or simply beer game is an easy-to-learn and well-known game that replicates the key features of real-world supply chains, while being useful for testing behavioural factors of decision making in supply chains (Croson et al., 2014). It is a common understanding that participants in the game usually underweight such parameters as inventory, supply line and demand information, which diverges their ordering decisions from overall optimum order quantity in different periods of the game and subsequently causes the bullwhip effect (Croson & Donohue, 2006; Narayanan & Moritz, 2015; Sterman, 1989b). In this paper we are investigating the attitudes of participants toward risk and whether this affects their decision making.

Beer game consists of four echelons (factory, distributor, wholesaler, and retailer). Each echelon is played individually by a participant. Every week participants receive a particular amount of demand from their downstream supply chain echelon, and make decisions about the order quantity by considering the costs of inventory and backorders and the levels of on-hand and on-order inventory. More information about the standard settings of the game are provided by Sterman (1989b) and Croson and Donohue (2006).

Aligned with the previous studies, for distributor, wholesaler, and retailer echelons we considered an overall 4 weeks of delay from when an order is placed (2 weeks delay) to when the order is received by the same echelon (2 weeks delay). This amount is 2 weeks in total for the factory. Customer demand for all sub-treatments of the beer game followed the uniform distribution of 0 and 8 ($U(0,8)$). The beginning on-hand inventory amount was 8 units. On-order inventory quantity in week 1 equalled 16 units (4 units for each week of delay) for distributor, wholesaler, and retailer and 8 units for the factory.

To test our propositions, we needed to have sub-treatments of the beer game representing supply chains in practice with both revenue and costs parameters, and also the traditional beer game with only cost parameters of inventory and backorders. For the former, we initially used $r = \$5/\text{unit}$ of sales as a source of revenue for every unit of demand that is satisfied every week. The cost parameters were $h = \$0.5/\text{unit}$ of inventory and $b = \$1/\text{unit}$ of backorders for every week of the game. For the traditional beer game, we used the settings proposed in earlier studies for a standard beer game with $h = \$0.5/\text{unit}$ of inventory and $b = \$1/\text{unit}$ of backorders for every week of the game.

Subjects participated in an online version of the beer game developed for the classroom use (see Appendix 4 for the game interface and instructions). Participants in the loss and gain sub-treatments of the game were full-time undergraduate students of University of Houston (UH) and full-time MBA students of Macquarie Graduate School of Management (MGSM). The majority of students for all the sub-treatments were males. Most participants in all sub-treatments of the game did not have prior experience of playing the beer game. The winner group in each of the four games won \$200 in cash (\$50 each player). Table 3.5 summarizes some of the game settings and conditions for the aforementioned four sub-treatments.

Table 3.5 Summary of the four sub-treatments

	Sub-treatment 1 (Loss game)	Sub-treatment 2 (Gain game)
Information sharing	No	No
Demand distribution	U (0,8)	U (0,8)
Initial on-hand inventory (units)	8	8
Lead time (retailer, wholesaler, distributor)	4 weeks	4 weeks
Lead time (factory)	2 weeks	2 weeks
Postgraduate*	81%	22%
Female	33%	35%
School	MGSM/UH	MGSM/UH
Participants (decision makers)	192	192
Participants (teams)	48	48
Played beer game before (decision makers)	14	47
Berlin Numeracy Test score (Average)		
First quartile (% of Groups)	27	20
Second quartile (% of Groups)	37	43
Third quartile (% of Groups)	24	20
Fourth quartile (% of Groups)	12	17

* Others are undergraduate students.

Prior to playing the game, we collected participants' demographic and risk profile data through a short survey. We used the measures introduced in the Berlin Numeracy Test (Cokely, Galesic, Schulz, Ghazal, & Garcia-Retamero, 2012) to gain an understanding of the subjects' statistical numeracy and risk literacy. Statistical numeracy is one of the main causes of risk literacy, which accounts for an accurate interpretation of information about risks and acting on them (Cokely et al., 2012). Berlin Numeracy Test is argued to be one of the strongest predictors of statistical numeracy and risk literacy beyond other tests for cognitive ability and numeracy. The pre-game survey is presented in Appendix 5. Using the computer adaptive version of the test, we categorized the subjects in four quartiles, with subjects correctly answering to 3–4 questions in the fourth quartile and subjects correctly answering only 0–1 questions in the first quartile. Subsequently, we assigned every four subjects in the same quartile to one group for playing the game. If there were insufficient subjects in one quartile for a beer game group, we used subjects in the closest two quartiles to form the group.

Results

Initial analysis

Before starting the data analysis for the presence of the bullwhip effect, we eliminated the outliers, that is, games with very high overall costs or ordering standard deviations, to increase the accuracy of the results obtained from testing our propositions. Next, we tested the two sub-treatments of the beer game for the presence of the bullwhip effect. To test for the bullwhip effect, we measured the order amplifications through the increase in standard deviations of orders from a downstream to an upstream supply chain echelon so that $\sigma_{upstream} > \sigma_{downstream}$ (Chen, Drezner, Ryan, & Simchi-Levi, 2000; Croson et al., 2014). We used Wilcoxon Signed-Rank Test (Wilcoxon, 1945) to make the comparisons. The null hypothesis of this test is that the median differences of the paired data are zero. The advantage of this test over the Sign Test (Siegel, 1956) is that, in addition to the direction of the changes between the paired data, the significance of the changes from zero is also considered.

Overall, the bullwhip effect was observed for all the games (Table 3.6). For both loss and gain games an overall 81% of cases showed amplifications in standard deviations of orders ($\sigma_{upstream} > \sigma_{downstream}$) with the amplifications also being significant among various supply chain tiers.

Table 3.6 Order amplification comparison

	Overall	Distributor vs.	Wholesaler vs.	Retailer vs.

		factory	distributor	wholesaler
Loss game				
Success rate (%)*	81	90	75	79
P-value†	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Gain game				
Success rate	81	82	81	80
P-value	$p < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.001$

* Number of cases with $\sigma_{upstream} > \sigma_{downstream}$/Total number of cases

† Wilcoxon signed rank test

The average and standard deviations of order for all the games are presented in Table 3.7. Overall, average order quantities and their standard deviations were higher for factory and distributor than for wholesaler and retailer echelons. There were no specific differences in order variations between the games with revenue parameter, compared with traditional beer game with only loss parameters.

Table 3.7 Ordering variability by echelon

	Factory		**Distributor**		**Wholesaler**		**Retailer**	
	Order (Average)	order (S.D.)	Order (Average)	order (S.D.)	Order (Average)	order (S.D.)	Order (Average)	order (S.D.)
Loss game ($n = 48$)*	8.41	15.92	7.61	11.32	5.93	6.96	4.35	3.8
Gain game ($n = 48$)	10.61	17.63	10.15	13.34	6.72	8.36	4.33	3.95

* Total number of groups for each sub-treatment.

Optimum order analysis

Initially, we compared orders placed by subjects ($O_{i,t} = q$) with optimal order quantities (q^*) for the loss and gain sub-treatments of the beer game and by echelon. To this end, we used (4) and, considering the lag of four weeks from ordering to receiving the inventory, we have $l = 4$ and we obtain q^*. Table 3.8 shows that subjects tended to order more than q^* in the gain game, whereas in the traditional beer game with only loss parameters, subjects ordered less than q^*.

Table 3.8 Actual orders vs. optimum orders by echelon * †

	Negative ranks††	Positive ranks	Ties	Total (n)	(p-value)
Loss game					
Factory	370	852	506	1728	$p < 0.001$
Distributor	539	752	437	1728	$p < 0.001$
Wholesaler	607	714	407	1728	$p < 0.001$
Retailer	664	800	264	1728	$p < 0.001$
Overall	2180	3118	1614	6912	$p < 0.001$
Gain game					
Factory	598	584	546	1728	$p < 0.05$
Distributor	683	553	492	1728	$p < 0.001$
Wholesaler	839	462	427	1728	$p < 0.001$
Retailer	787	641	300	1728	$p < 0.001$
Overall	2907	2240	1765	6912	$p < 0.001$

* To calculate q^* using (4), the value for desired on-hand and on-order inventory (S') for distributor, wholesaler, and retailer is equal to 24 (8 units of initial on-hand inventory and 16 units of initial on-order inventory), while this value for factory is 16 (8 units of initial on-hand inventory and 8 units of initial on-order inventory).

† Wilcoxon signed rank test is used for all comparisons.

†† Negative rank is indicative of actual order being larger than the optimum order.

For testing the propositions in the *Model Development* section (see page 132), we first investigated the results of gain and loss games with regards to the pre-defined intervals in our proposed models. The results of this analysis for the loss and gain games are presented in Table 3.9.

Table 3.9 Actual orders vs. optimum orders by echelon with pre-defined intervals*

	Negative ranks†	Positive ranks	Ties	Total ($\mathbf{n}$)	($\boldsymbol{p}$-value)
Loss game					
$w < w_0$					
$I \geq D$	1351	1643	1515	4509	$p < 0.001$
$I < D$	829	1475	99	2403	$p < 0.001$
Gain game					
$w \geq w_0$					
$I \geq D$	1599	1223	663	3485	$p < 0.001$
$0 \leq I < D$	192	331	8	531	$p < 0.05$
$w < w_0$					
$I \geq D$	560	31	1047	1638	$p < 0.001$
$0 \leq I < D$	41	78	2	121	$p < 0.05$
$I < 0$	515	577	45	1137	$p < 0.05$

* Wilcoxon signed rank test is used for all comparisons.

† Negative rank is indicative of actual order being larger than the optimum order.

Table 3.9 shows that in the loss beer game and for both cases of $I \geq D$ and $I < D$ the orders placed by subjects were significantly lower than the optimum order. This finding is only partially aligned with the predictions of risk seeking and loss-aversion models (see Table 3.4 and Table 3.10).

Looking at the results of order analysis for gain game and the non-negative profit condition, when $I \geq D$, orders placed by subjects are significantly higher than the optimum order quantity. This violates the predictions of risk aversion and PT models.

Moreover, when $0 \leq I < D$, orders placed are significantly smaller than optimum order quantity.

For the negative profit condition $w < w_0$, Table 3.9 shows that when $I \geq D$, subjects preferred to order more than optimum. Also, with the exception of $I < 0$, $q \leq q^*$ when $I < D$. Overall the outcomes of both positive and negative profit conditions partially confirm only the predictions of the risk-aversion and risk-seeking model. Table 3.10 summarizes these findings.

Table 3.10 Summary of the findings *

	$w \geq w_0$		$w < w_0$		
	$I \geq D$	$0 \leq I < D$	$I \geq D$	$0 \leq I < D$	$I < 0$
Loss game					
Risk aversion and risk seeking	N/A	N/A	×	✓	✓
Loss-aversion	N/A	N/A	✓	×	×
Prospect Theory	N/A	N/A	Inconclusive	Inconclusive	Inconclusive
Gain game					
Risk aversion and risk seeking	×	×	✓	✓	✓
Loss-aversion	N/A	N/A	×	×	×
Prospect Theory	×	×	Inconclusive	Inconclusive	Inconclusive

Additional analysis

Previous studies have investigated several behavioural and non-behavioural factors that could underlie the variations in ordering behaviours in supply chains. For instance, Narayanan and Moritz (2015) collected data on subjects' intelligence, risk literacy, risk preferences, age, gender, and supply-chain-related work experience and found no significant differences for any of the behavioural factors or the other covariates that could explain differences in the beer game performance. However, despite using non-parametric tests, the authors acknowledged that a small sample size could be an underlying cause of not achieving significant results for any of the categories.

For the newsvendor problem, Bloomfield and Kulp (2013) found little evidence that cognitive ability, impulsiveness or locus of control impacts ordering decisions. de Véricourt, Jain, Bearden, and Filipowicz (2013) studied the differences in ordering decisions of males and females and found that, in certain settings with high profit margins, males on average ordered more than females.

In this study, we compared the average and standard deviations of orders for each participant based on their BNT scores, sex, age, work experience and type of game played. For the BNT scores, and similar to the categorization proposed by Narayanan and Moritz (2015), we assigned the overall score of 2 as a high score. We defined two age groups of above 30 and below 30 years, and for work experience we considered supply-chain-related work experience. The results of comparisons are summarized in Table 3.11. Both a parametric T-test and a non-parametric Mann-Whitney U test for independent samples were applied to analyse and validate the results.

Results in Table 3.11 show no significant difference for average and standard deviations of orders placed for sex, age and related work experience. The results obtained for age and work experience confirm the findings of previous studies (Bloomfield & Kulp, 2013; Croson, 2007; Narayanan & Moritz, 2015). The results for BNT scores are significant and show that subjects with high BNTs (above 2) performed much better in the beer game, with their average ordering being closer to 4 and having much lower standard deviations. Participants also tended to order in larger amounts on average when they were playing a gain game.

Table 3.11 Beer game performance based on behavioural and non-behavioural factors

	Mann-Whitney U Test (Mean Rank)		T-Test (Mean)	
	Average Order	S.D.	Average Order	S.D.
BNT				
High ($n = 166$)	175.280	166.970	6.054	7.528
Low ($n = 217$)	204.790	211.147	8.322	12.555
P-value	$p < 0.05$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Sex				
Female ($n = 131$)	196.557	205.813	7.603	11.154
Male ($n = 252$)	189.631	184.819	7.202	9.972
P-value	$p = 0.553$	$p = 0.078$	$p = 0.534$	$p = 0.345$
Age				
Below 30 ($n = 291$)	193.192	192.118	7.601	10.625
Above 30 ($n = 92$)	188.228	191.625	6.511	9.588
P-value	$p = 0.702$	$p = 970$	$p = 0.127$	$p = 0.456$
Work experience				
No ($n = 195$)	201.549	197.602	7.743	10.957
Yes ($n = 188$)	192.096	186.189	6.920	9.774
P-value	$p = 0.079$	$p = 0.313$	$p = 0.178$	$p = 0.319$
Game				
Loss ($n = 190$)	176.195	182.155	6.632	9.568
Gain ($n = 193$)	207.560	201.692	8.036	11.172
P-value	$p < 0.05$	$p = 0.084$	$p < 0.05$	$p = 0.177$

Conclusions and limitations

This paper investigated the behaviour of supply chain decision makers toward risks and how it affects their ordering decision. To this end, we studied risk-aversion/risk-seeking, loss-aversion and prospect theory models, and the compatibility of their predictions with the empirical results of the behavioural experiments. This study produced six main findings:

1. Risk-aversion and risk-seeking models can only partially predict ordering behaviour, and especially when subjects incur losses.
2. Loss aversion cannot predict the ordering behaviour of participants in multi-echelon supply chains.
3. Prospect theory is inconclusive about ordering behaviours and therefore cannot be used to make predictions about ordering decisions in supply chains.
4. None of the models predicted the results in games with the addition of the revenue parameter.
5. Subjects with higher scores in the BNT test performed better in the games. No significant differences were observed in the performance of participants according to their sex, age or relevant work experience.
6. Overall, when the outcomes were all losses (loss game), subjects tended to under-order, whereas when the outcomes could be both gains and losses (gain game), subjects were more inclined to over-order.

All research has its share of caveats and ours is no exception. First, we did not use the decision weights of the prospects in our model. The main reason behind this was the abundance of different prospects at each period of the game which culminates in the estimations of their probabilities to be inaccurate. Moreover, each game and supply chain tier would have had different prospects at each stage of the game, and this would make the inclusion of decision weights even more complicated. Future research could be conducted in a more controlled beer game setting with only a handful of prospects available to the subjects so that estimations of decision weights will be possible.

Second, for our modelling section we did not include the ordering decision rule by Sterman (1989b), or the alternative simplified model proposed by Croson and Donohue (2006) that accounts for subjects' bounded rationality in terms of underweighting quantities of inventory, demand or supply line. There are several reasons behind this decision. First, it could be mathematically shown that the parameters introduced in the aforementioned studies for ordering decisions do not affect the predictions of our analytical models in the *Model Development* section (page 132). Second, mixing those models with either one of the risk models used in this study would add at least one more parameter (α, λ or both) for estimation. As a rule of thumb, this would add at least 10 weeks to the existing 36 weeks' duration of the beer game in order to make sufficient observations for parameter estimation and model fit comparison. The latter could be investigated as a separate research article in the future.

3.4 Chapter summary and conclusion

The first paper presented in this chapter investigated the intersection between operational and behavioural risks, and how they could be incorporated in operations research analytical models and, more specifically, DEA models.

The second paper focused only on the emerging field of behavioural supply chain and operations management, and looked particularly at the attitudes of decision makers toward risk and their impact on inventory decisions in multi-echelon supply chains.

For both papers a multi-method approach was used to better capture the essence of human behaviour, its anomalies and its impact on supply chain operations. The first paper used a mix of semi-structured interviews and analytical modelling to assess a number of service supply chains in terms of several operational factors and behavioural risks having a diverse effect on these operational factors, hence causing operational risks. The second paper used analytical modelling and behavioural experiments to see the compatibility of the model predictions with empirical results with regards to the research propositions.

Overall, both papers aimed to highlight the role of incorporating behavioural risks, and the attitudes of decision makers toward risks, both of which could have substantial impacts on the quality of overall supply chain processes.

-CHAPTER FOUR-

-Risk and Vulnerability in Service Triads-

4.1. Introduction

So far our discussions surrounding supply chain risk identification and assessment have been constrained to the traditional types of supply chains with a vertical structure from the customer to the supplier. However, it has been well argued that in extended supply networks that do not necessarily follow the linear format of supply chains, the smallest building blocks of the network that represent the features of the whole supply network – in terms of interrelations between supply network members – are the triads (Choi & Wu, 2009a). Studying risk and vulnerability in triads in general, and in service triads in particular, helps better understand the risks emerging in the interrelations between different members of supply networks and specially suppliers and customers. In service settings, and when certain services are outsourced by the buyers to external suppliers, the interactions between the suppliers and customers increase significantly, which makes buyers (i.e., outsourcing company) vulnerable to a whole new set of risks (e.g., Li & Choi, 2009a) that are different from the conventional operational and behavioural risks so far argued.

The two studies presented in this chapter investigate various structural forms of triads, in which risks could emerge and propagate. A graph theoretical approach is used to assess the vulnerability levels in the identified triads. Moreover, a case study in the banking service supply chains illustrates how the triads and vulnerability assessment in them could help supply chain decision makers prioritize the most vulnerable links and members in a supply network.

4.2. Book chapter (Document 7): Modelling risk emergence and propagation in buyer-supplier-customer relationships[7]

ABSTRACT The present study aims to identify and formalize the structural and relational patterns, which account for risk emergence and propagation in buyer-supplier-customer service triads. Following the guidelines of the design science research approach and based on the existing literature, buyer-supplier-customer service triads are categorized into a coherent typology according to the role that each supply chain dyad plays in the emergence and propagation of risk within the triad it forms. In the context of this study, such triads are referred to as Risk-aware Service Triads (RaSTs). To explore all the feasible forms of RaSTs, including the ones that have not yet been addressed in the literature, this study adopts the formalism of weighted directed graphs. As a result, a typology based on thirty different types of RaSTs is suggested. This typology allows: (i) to systematize and formally represent a variety of hypothetical scenarios when each of the dyadic structures within buyer-supplier-customer service triads acts as risk trigger, risk taker or risk neutral component of the respective RaST; and (ii) to calculate the maximal and minimal risk index specific to each of the identified type of RaST, thereby facilitating the identification and assessment of risk exposures associated with buyer-supplier-customer service triads. An illustrative example of how the methodological approach underlying the suggested RaST typology facilitates risk assessment in service triads and service networks is presented.

Keywords: buyer-supplier-customer service triad, risk-aware service triad (RaST), RaST typology, graph theory

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[7] Rotaru, K., & **Pournader, M.** Modeling Risk Emergence and Propagation in Buyer-Supplier-Customer Relationships: Towards a Typology of Risk-aware Service Triads. In Y. Khojasteh (Ed.), *Supply Chain Risk Management: Advanced Tools, Models, and Developments*. Springer (Forthcoming Oct. 2016).

Introduction

Globalization and the recent technological advancements coupled with the need to cut costs and gain competitive advantage in an increasingly volatile global marketplace have resulted in a dramatic increase in outsourcing levels by servicing companies, looking for further means of cost reduction and efficiency improvement (Gunasekaran & Kobu, 2007). In view of the growing complexity of modern, highly diversified supply chains, the inherent linearity underlying the traditional focus on the dyadic relationships between the members of a supply chain does not allow to capture the nature of the properties, emerging within more complex supply chain networks (Choi, Zhaohui, Ellram, & Koka, 2002; Wu, Choi, & Rungtusanatham, 2010). To provide a more realistic account of the network structure and inherent characteristics of the modern supply chains, a number of studies suggested shifting the focus towards the elementary form of the supply chain network: a supply chain triad (Finne & Holmström, 2013). This was followed by a call for further investigation into the structural and relational characteristics of service triads (Holma, 2012), including the study of risks causing failure in outsourcing practices (Bastl, Johnson, & Choi, 2013; Choi & Wu, 2009b).

Since the earlier articles introducing triadic relationships in the context of supply chain management (e.g., Choi et al., 2002), the literature has reported on the following common types of supply chain triads including: *buyer-supplier-customer* (e.g., Niranjan & Metri, 2008b; Rossetti & Choi, 2005b), *buyer-supplier-supplier* (Wu et al., 2010), and *buyer-buyer-supplier* (e.g., Choi & Kim, 2008). Notably, most of these studies investigate the supply chain triads operating in manufacturing rather than services domain. Hence, the focus of this study is on a relatively less investigated form of supply chain triads, the ones supporting the service outsourcing processes (Li & Choi, 2009b; Niranjan & Metri, 2008b).

To date, the literature exploring the patterns of risk emergence and propagation in the context of buyer-supplier-customer service triads has been limited but growing (Wynstra, Spring, & Schoenherr, 2015). Despite a number of attempts to represent the underlying factors that account for adverse behaviours by triad members (e.g., Bastl et al., 2013; Choi & Wu, 2009b), the literature on supply chain triads still lacks a systematic approach that would categorize risks according to where within supply chain triads these risks emerge and what are the possible pathways for their propagation between the member organizations of the supply chain triads. To the best of our knowledge, no research study has attempted to develop a generic typology outlining the core relational properties in buyer-supplier-customer service triads service triads and, using this information, to attribute corresponding generic risk profiles to the types of supply chain triads being analysed. In this regard, a number of studies could be outlined as conducting the assessment of relational properties in supply chain service triads with the view to better understand the performance drivers in the triadic relationships. Peng, Lin, Martinez, and Yu (2010a) used social networks to study cooperative performance of service triads, while Holma (2012) borrowed from social capital theory to investigate interpersonal interactions and their effects on service triads. Depending on the initiating party, Wynstra et al. (2015) identified three types of service triads – 'buyer-initiated', 'customer-initiated' and 'supplier-initiated' – and outline a number of characteristics for each of these types, including: initiating party, focal service provider, service user (beneficiary), as well as who are the providers of inputs for the focal service. While the suggested typology serves as a generic framework to consider some of the properties of the service triads, it does not provide any formal mechanism of informing the user about either the performance drivers or the risk profile of the service triads being investigated through the prism of the suggested typology.

To address this research gap, the present study seeks ways to categorize the identified generic patterns reflecting the emergence and propagation of potential adverse events and behaviours within buyer-supplier-customer service triads into a comprehensive typology. Specifically, the concept of risk-aware service triads (RaSTs) is introduced to outline and categorize relational and structural properties of buyer-supplier-customer interactions that account for the increased levels of risk exposure within a given buyer-supplier-customer service triad. It is also expected that a greater clarity around the risk patterns delineated by RaSTs would facilitate the evaluation of the risk levels according to the identified types of RaSTs. Accordingly, the aim of this study is threefold: (i) to identify and formalize the structural and relational patterns which account for risk emergence and propagation in buyer-supplier-customer service triads; (ii) to design a coherent typology for classification of the modelled RaSTs according to the nature of their implicit mechanisms of risk emergence and propagation within the triads; and (iii) based on the suggested RaST typology, to suggest an approach for evaluation of the inherent risks associated with each RaST type.

Using guiding principles of design science research approach (Holmström, Ketokivi, & Hameri, 2009; van Aken, 2004) and the modelling apparatus of graph theory in supply chains (Borgatti & Li, 2009; Kim et al., 2015), thirty types of RaST models are developed and categorized within a coherent RaST typology. Each RaST model has been ranked according to its implicit Risk Index (RI), which represents a quantitative measure of risk associated with the structural relationships among the members of a given RaST. Therefore, the taxonomy of RaST models, as well as the underlying approach for categorizing supply chain service triads according to their inherent risk profile, provide a comprehensive tool for risk assessment of triadic relationships that match specific RaST types outlined in the RaST taxonomy. We apply the suggested RaST taxonomy to review recent articles on buyer-supplier-customer service triads, and specifically to categorize the relational properties and risks categorized in these articles. This allows us to identify the types of RaSTs that have been overlooked in this emerging body of literature but still impose risks that threaten the objectives of supply chain partners operating within service triads, as well as service triads seen as complex adaptive systems. With the view to justifying the relevance of the proposed RaST typology, we use an illustrative example of the application RaSTs to assess risks in service triads and subsequently in service supply networks.

The remainder of this chapter is organized as follows. In the next section we provide a brief background by discussing the properties of service triads, specifically focusing on the phenomenon of risk emergence in the context of service triads. We then outline the research method built upon the design science, adopted as a research approach that guides the process of building RaST typology, and graph theory adopted as a modelling methodology. Subsequently, in line with the principles of design science and using the toolset of graph theory, a range of RaSTs types are suggested and categorized into three groups based on the nature of the risk and emergence mechanisms reflected in each RaST types. The identification of groupings and types of RaSTs is supported by a detailed review of the literature on buyer-supplier-customer service triads. Based on the properties of the directed graphs associated with each individual RaST type, a risk index is calculated following a formal procedure reported in operations and supply chain management. Next, the relevance of the suggested RaST typology is justified by showing how the proposed RaSTs can facilitate risk assessment in service triads and more complex service networks. Finally, the chapter is concluded by outlining a number of research limitations and discussing the core future research directions triggered by this study.

Background

The enhanced ability to respond to changes in demand and to the opportunities that may emerge, often goes hand in hand with the increasing dependency on quantum of work outsourced by servicing companies to their suppliers leading to an extension of the supply chains in both size and complexity (Ellram et al., 2008; Tate, Ellram, & Brown, 2009b). Along with the increasing profit margins and other performance improvement outcomes achieved through the growing complexity and dynamism of the modern supply chains, comes the issue of the increased vulnerability of the supply chains and their individual members (Wagner & Bode, 2008).

Having in mind the purpose of a desirable level of services delivered, service providing companies seek to establish proper relationships with members participating in the outsourcing practices considering such relationships as the key for achieving this purpose (Bastl, Johnson, Lightfoot, & Evans, 2012a). As a result, the companies today are urged to establish additional forms of risk response strategies and control procedures as part of their profiles to avoid the emergence of new sets of risks including adversarial buyer-supplier relations or winning customers over by suppliers, to name a few (Choi & Kim, 2008). A considerable amount of risks threatening supply chains, including service supply chains and their individual service triads, are context-specific, that is, their probability and magnitude largely depend on the structural characteristics of the operational context where they emerge (Neiger et al., 2009). Both emergence and propagation of these risks across organizational boundaries largely depend on the structural characteristics of the supply chain network and the nature of the relationships of its members (Bellamy & Basole, 2013; van de Valk & van Weele, 2011). To understand better these characteristics some general properties of the service triads are discussed below.

A service triad is commonly regarded as an independent elementary form of a service supply chain network that shares certain structural and behavioural characteristics of the network (Niranjan & Metri, 2008b). The term 'possible tie(s)' used in (Wasserman & Faust, 1994) the definition of triads by Wasserman and Faust (1994), implies up to six different types of triads built on a continuum of inter-organizational relationships from less to more connected members (see Peng et al., 2010a). While such view could be applicable to the study of manufacturing triads, in the context of service triads, where there is an ongoing interaction taking place between the members of the triad (Li, 2011; Li & Choi, 2009b), such diversity of relationships is unlikely. It thus becomes of an utmost importance to take into consideration all three bidirectional relationships of service triad members in order to determine the possible risk propagation within the triad as well as the triad's degree of risk exposure. This concern has been addressed in the following sections that address the development of the RaST typology.

Service triad as an elementary form of supply chain network possesses the characteristics of a complex adaptive system whose behaviour is determined by the activity of agents that are part of this system. Thus, a service triad exhibits unique characteristics or emergent properties, which are not properties of its distinct components but the whole network (Bastl et al., 2013). This view implies inherent qualitative and quantitative differences in risk profile of a service triad when compared to the sum of the risk profiles of the individual members of the triad, even if the dyadic relationships of each individual member is taken into account when conducting such risk assessment. Thus, in the context of buyer-supplier-customer service triads, new risk types emerge which are neither inherent properties of the distinct members of these types of triads nor their dyadic relationships but refer to the relationships between all the members within the network.

The need to account for the interactions among all members of service triads when assessing their risk exposures precludes researchers and practitioners to directly adopt the heuristics and more formal methods of risk assessment applicable in the context of risk analysis of single organizations or their dyadic relationships. At the same time, the literature investigating the issues of risk modelling/assessment in the context of service triads is still scarce. One of the examples is the study by Li and Choi (2009b) who adopted the social network theory lens to highlight an emerging condition implying that in time and upon building some confidence, a customer may find it more comfortable working directly with the supplier without the buyer being involved. This phenomenon deprives buyer of the benefits of being the sole intermediary between customer and supplier (Peng et al., 2010a; Rossetti & Choi, 2005b) and delegate the associated competitive advantages (i.e., information benefit and control benefit) to the supplier. These transitions in the triadic relations of buyer-supplier-customer are referred to as 'bridge decay' and 'bridge transfer' conditions. Another example is the study by Niranjan and Metri (2008b) who identified the underlying premises of the ties in 'client-vendor-consumer' triad addressing issues that arise from insufficient and unsatisfying levels in the quality of the services provided.

Despite the first steps that have been made in the literature to explain and document a number of mechanisms associated with risk emergence and propagation within service triads, and specifically buyer-supplier-customer service triads, to the best of authors' knowledge no comprehensive approaches have been suggested to widen the scope of such investigation beyond the boundaries of the single case studies. Specifically, no theoretically grounded approaches have been suggested to support reasoning about the potential risk scenarios associated with service triads, considering the nature of potential vulnerabilities in the relationships between the members of these triads. Thus, a comprehensive typology, which would allow to formally represent and categorize such scenarios based on a variety of factors involved, as well as on the risk ratings assigned to each individual scenario, is introduced further as a viable solution to address this research gap. Below we present the research method supporting the design of such typology.

Research method

In this study, the design science research approach is adopted to guide the identification and categorization of the structural and relational patterns underlying risk emergence and propagation in buyer-supplier-customer service triads, whereas graph theory is used as a modelling methodology that supports the development of the RaST typology.

Design science research approach

Design science has a long history as a set of pragmatic principles underlying the invention of novel artifacts based on a previously acquired technological knowledge, and as such, it is not t a discipline-specific approach to knowledge building. It has been widely adopted in the fields of information systems and computer science where it was reported to assist in understanding, explaining and frequently improving the behaviour of existing systems by creating innovative and unique artifacts in a well-defined manner or by analysing the use and performance of the designed artifacts. The design science approach has also been adopted in organizations science (van Aken, 2004), operations and supply chain management (Holmström et al., 2009), and specifically supply chain service triads (Finne & Holmström, 2013). Applied to operations and supply chain management, design science is introduced as an approach aiming primarily at discovery and problem solving, and emphasizing the novelty of the knowledge generated as a product of the design process (Holmström et al., 2009). In doing so, design science provides a utility-oriented methodology for addressing business needs through a purposeful design of an artifact or intervention (van Aken, 2004, p. 226). These needs can be represented in terms of desirable properties that give a purposeful dimension to the process of artifact building.

In the context of this study, the design science research approach is used to support the formulation of our novel artifact, the RaST typology, which so far has not been suggested in the research literature or practice. Thus, we see the end product of the design process as a set of technological rules, each formalizing a unique configuration of a RaST model according to the innate characteristics of risk emergence and propagation associated with each individual type of a buyer-supplier-customer service triad. To guide the design of the RaST typology we conduct a literature review on service triads, their reported typology and the nature of the dyadic relationships they are composed of. We then adopt graph theory as a modelling method that supports the development of a set of technological rules suggested to formulate the desirable artifact. We formalize the relational properties between supply chain dyads, which form part of the triadic structures and account for the emergence and propagation of risks within buyer-supplier-customer service triads. Then, as part of our design process which follows Holmström and Romme (2012), the risk trigger, risk taker or risk neutral roles of the pairwise inter-organizational relationships between the members of buyer-supplier-customer service triads are formulated. This allows for the formal definition and categorization of the relational factors, or technological rules, introduced in this study that increase the probability of risk events in these triads (figures 3.1–3.3). Next, RaSTs, which have been identified and categorized into RaST typology are justified by demonstrating the relevance of the specific RaST models matching them with the evidence reported in the research literature (Table 4.1).

Graph theory: A modelling methodology for designing RaSTs

The versatility of graphs in modelling the relationships between members of networks has made them widely applicable in social, technological, informational and biological networks (Borgatti & Li, 2009; Wasserman & Faust, 1994). In their recent review of the studies adopting network analysis approaches in the context of supply chain management, Borgatti and Li (2009) and Bellamy and Basole (2013) distinguish a number of promising research directions among which is the application of the graph theoretical approach to model the network structure and relevant properties of supply chains. The applicability of graph theory to modelling supply chain risks has been recently confirmed in the literature (Wagner & Neshat, 2010).

The simplest mode of a graph is comprised of a set of vertices linked by edges. In more complex graphs, the vertices could each represent a particular feature, identity or entity

(West, 2001). Similarly the edges could also be directed and/or have weights. The graph theory is adopted in this study to assist in modelling of a range of risks that stem from the bidirectional relationships between the members of a supply chain triad. The risks under consideration include those that are triggered by an external event pertaining to dyadic cross-organizational process(es) within the service triad and then propagate further, affecting other dyadic relational aspects within the triad. Hence, in line with the graph theory, it is suggested that the RaSTs can be modelled as weighted directed graphs in which the vertices represent either buyer, supplier or customer and the directed edges illustrate the risk transferred from one vertex to the other.

RaST typology: Groupings and types of RaSTs and their risk ratings

In line with the graph theoretical approach, the pairwise relationships between the distinct members in buyer-supplier-customer service triads are categorized as follows:

1. *Risk trigger dyad*: the dyadic relationship among two vertices (i.e., buyer-supplier, or supplier-customer, or buyer-customer), which transfers risk to another dyad.
2. *Risk taker dyad*: the dyadic relationship among two vertices, which is exposed to risk by a risk trigger dyad.
3. *Risk neutral dyad*: the risk neutral dyad is not affected by risks that emerge in the risk trigger dyad and propagate within the risk taker dyad.

The risk trigger, risk taker and risk neutral dyads in figures 4.1-4.3 are illustrated by a dotted unidirectional arrow, non-dotted bidirectional arrow, and a continuous line respectively. The direction of the arrow in the risk trigger dyad depicts the adverse effect(s) of risk(s) imposed from one member of the dyad to another. A bidirectional arrow of the risk taker dyad indicates that both members in a particular type of dyadic relationship are exposed to risks by a risk trigger dyad.

All three groups of RaSTs discussed next should comprise at least one risk trigger and one risk taker dyad. This condition assures the presence of at least one inter-organizational risk affecting the service triad under investigation.

Group 1 (1 Risk Trigger/ 1 Risk Taker/ 1 Risk Neutral) of Buyer-Supplier-Customer RaSTs

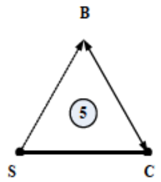
The first group of the RaSTs encompasses all three different types of the above-mentioned dyadic relationships (Figure 4.1). Triads in this group have a unique feature characterized by a risk neutral dyad. This indicates that regardless of the presence of mutual risk(s) between two members of the triad, the relationship between the third member and either one of the first two members sharing the risk remains unaffected.

Figure 4.1 Group 1 (1 Risk Trigger /1 Risk Taker/ 1 Risk Neutral) of RaSTs

$$A_1 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad A_2 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad A_3 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad A_4 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 101 \quad Max\ RI = 101 \quad Max\ RI = 101 \quad Max\ RI = 101$$

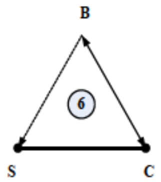
$$Min\ RI = 2 \quad Min\ RI = 2 \quad Min\ RI = 2 \quad Min\ RI = 2$$



$$A_5 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

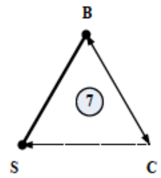
$$Min\ RI = 2$$



$$A_6 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

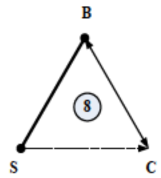
$$Min\ RI = 2$$



$$A_7 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

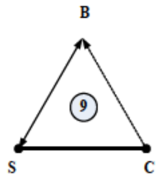
$$Min\ RI = 2$$



$$A_8 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

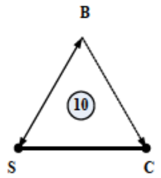
$$Min\ RI = 2$$



$$A_9 = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

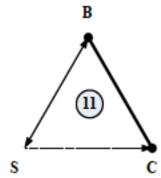
$$Min\ RI = 2$$



$$A_{10} = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

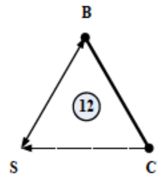
$$Min\ RI = 2$$



$$A_{11} = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

$$Min\ RI = 2$$



$$A_{12} = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 101$$

$$Min\ RI = 2$$

A ◄-----Risk Trigger Dyad (B-A)------- B

A -------Risk Trigger Dyad (A-B)----► B

A ◄—Risk Taker Dyad (A-B/B-A)—► B

A ●—Risk Neutral Dyad (A-B/B-A)—● B

(Buyer=B, Supplier=S, Customer=C)

$A_i, (1 = 1, \dots, n)$ in Figure 4.1 represents the adjacency matrix of the bilateral relations in service triads. Also RI represents the Risk Index in service triads. Further information on RI and how it is calculated is provided below and after introducing the types of RaSTs.

An example of this kind of relationship is RaST Type 8 indicating the bridge decay and bridge transfer case (Li & Choi, 2009b), where the supplier tries to solidify its bridge position by making stronger ties with the customer ('risk trigger' dyad). This type of risk is then imposed on the buyer-customer relationship ('risk taker' dyad) but does not have a negative impact on the buyer-supplier relationship ('risk neutral' dyad) (See Table 4.1). Figure 4.1 illustrates the twelve possible types of RaSTs in Group 1 along with their adjacency matrices and RIs which are going to be discussed in more detail after the introduction of all three groups of buyer-supplier-customer RaSTs.

Group 2 (2 Risk Triggers / 1 Risk Taker) of Buyer-Supplier-Customer RaSTs

Group 2 (Figure 4.2) contains two risk trigger dyads that impose risk(s) to the remaining dyad. There is no risk neutral dyad present in Groups 2 and 3. An instance of this group, RaST Type 18, is discussed by van der Valk and van Iwaarden (2011) and includes conflicting objectives in the buyer-supplier and supplier-customer relations (risk triggers), leading to negative impacts on buyer-customer relationship ('risk taker' dyad, further referred to as risk taker) (Table 4.1). Figure 4.2 illustrates the twelve possible types of RaSTs in Group 2 along with their adjacency matrices and RIs.

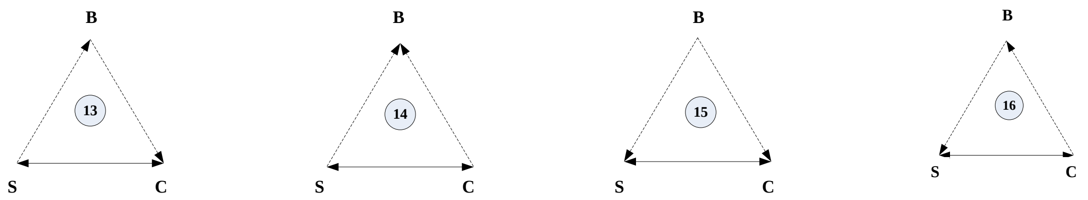
For instance for A_{13} in Figure 4.2, the RI is calculated using the formula in the Appendix 6 as below:

$$RI = 1 \times 1 \times 1 + 1 \times 1 \times 1 + 1 \times 1 \times 0 + 1 \times 0 \times 1 + 0 \times 1 \times 0 + 1 \times 1 \times 1 = 3$$

For all the RIs, we consider the main diagonal to be 1[8]. Also if we consider that the remainder of non-zero arrays having their highest values of 10 (according to the Likert Scale of 1-10), the max number obtained for RI is calculated as follows:

$$RI = 1 \times 1 \times 1 + 1 \times 10 \times 10 + 1 \times 10 \times 0 + 1 \times 0 \times 10 + 0 \times 10 \times 0 + 10 \times 10 \times 10 = 1101$$

Figure 4.2 Group 2 (2 Risk Triggers/1 Risk Taker) of RaSTs



$$A_{13} = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad A_{14} = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \quad A_{15} = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad A_{16} = \begin{matrix} B \\ S \\ C \end{matrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

A_{13}	A_{14}	A_{15}	A_{16}
$Max\ RI = 1101$	$Max\ RI = 101$	$Max\ RI = 101$	$Max\ RI = 1101$
$Min\ RI = 3$	$Min\ RI = 2$	$Min\ RI = 2$	$Min\ RI = 3$

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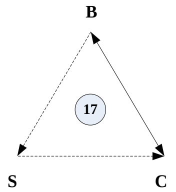
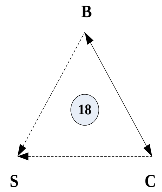
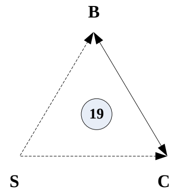
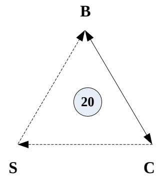
[8] For the matrices shown in figures 4.1–4.3, the values for all diagonals equal to 0 as the RaST models presented in these figures do not account for risks/vulnerabilities inherent in the processes of each node (i.e., each member of the supply chain triad). This assumption is dictated by the fact that the focus of the RaSTs depicted in these figures is on network risks (risks imposed by one RaST member to another). However, for the purpose of calculating the RIs, it is assumed that all the diagonals equal 1. Indeed, if the diagonal values are considered equal 0, this would result in 0 permanent for all RaSTs, thereby making problematic the calculation of the corresponding RIs. On the other hand, assuming the diagonal values equal 1 allows us to acquire meaningful (non-0) values for RIs and thus to compare the risk levels of different RaSTs.





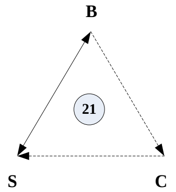


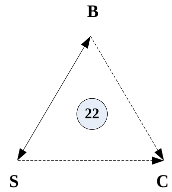


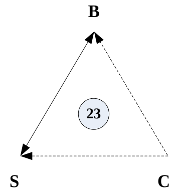
$$A_{17} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad A_{18} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix} \quad A_{19} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \quad A_{20} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix}$$

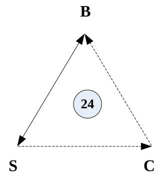
$$Max\ RI = 1101 \quad Max\ RI = 101 \quad Max\ RI = 101 \quad Max\ RI = 1101$$

$$Min\ RI = 3 \quad Min\ RI = 2 \quad Min\ RI = 2 \quad Min\ RI = 3$$









$$A_{21} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad A_{22} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \quad A_{23} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix} \quad A_{24} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 1101 \quad Max\ RI = 101 \quad Max\ RI = 101 \quad Max\ RI = 1101$$

$$Min\ RI = 3 \quad Min\ RI = 2 \quad Min\ RI = 2 \quad Min\ RI = 3$$

A ◄-------**Risk Trigger Dyad (B-A)**------- B

A -------**Risk Trigger Dyad (A-B)**-------► B

A ◄—**Risk Taker Dyad (A-B/B-A)**—► B

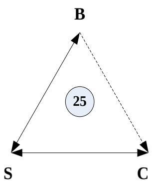
(Buyer=B, Supplier=S, Customer=C)

Group 3 (1 Risk Trigger/2 Risk Takers) of Buyer-Supplier-Customer RaSTs

Another possible configuration according to predefined conditions of buyer-supplier-customer RaSTs encompasses risk trigger dyadic relationships between two vertices that impose risk(s) to the remaining two dyads (risk takers). Figure 4.3 illustrates the remaining six possible types of RaSTs in Group 3 along with their adjacency matrices and RIs.

Carson, Carson, Knouse, and Roe (1997) argue that given the presence of a risk trigger dyad in a supply chain triad (Group 1), if not neutralized, it will soon affect the other dyadic relationships within this triad. According to this statement, RaSTs of Group 1 may potentially transform into RaSTs of Group 3 characterized by a higher level of hazard.

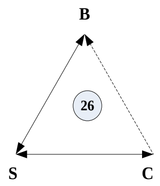
Figure 4.3 Group 3 (1 Risk Trigger/ 2 Risk Takers) of RaSTs



$$A_{25} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 1201$$

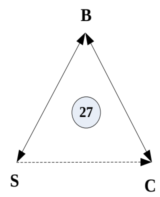
$$Min\ RI = 4$$



$$A_{26} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 1201$$

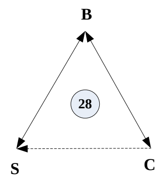
$$Min\ RI = 4$$



$$A_{27} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

$$Max\ RI = 1201$$

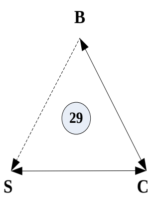
$$Min\ RI = 4$$



$$A_{28} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 1201$$

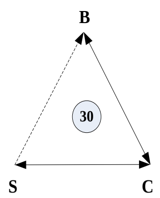
$$Min\ RI = 4$$



$$A_{29} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 1201$$

$$Min\ RI = 4$$



$$A_{30} = \begin{matrix} B \\ S \\ C \end{matrix}\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

$$Max\ RI = 1201$$

$$Min\ RI = 4$$

A ◄-------**Risk Trigger Dyad (B-A)**------- B

A -------**Risk Trigger Dyad (A-B)**-------► B

A ◄—**Risk Taker Dyad (A-B/B-A)**—► B

(Buyer=*B, Supplier=S, Customer=C)*

Further instructions on the application of the RaSTs

The graph models (RaSTs) specified in figures 4.1–4.3 exhibit a number of properties facilitating understanding, formalization, and quantification of the inherent risks:

1. The *Nodal-in degree* or *Nodal-out degree* of vertices represent the extents to which a vertex is subjected to risk(s) or imposes risk(s). These characteristics can be easily extracted by summation of the columns and rows of the adjacency matrix. According to the suggested typology of the triads, it is apparent that in the adjacency matrix comprised of arrays with the highest value of 1, the maximum *Nodal-in degree* or *Nodal-out degree* of each vertex could be 2. Thus, considering RaSTs in Group 1, and for instance RaST Type 1, if the supplier's vertex value has the *Nodal-in degree* = 2, it indicates that it has the highest exposure to risk(s). This concept is critical especially when there exists a complex network of suppliers, buyers and customers to be investigated (Bezuidenhout, Bodhanya, Sanjika, Sibomana, & Boote, 2011).
2. According to Wagner and Neshat (2012) the risk index (RI) of graphs or weighted graphs could be calculated using *matrix permanent*. The similar approach has been adopted in the literature that uses matrix permanent as an indicator of cost effectiveness (Sabharwal & Garg, 2013), effectiveness of risk mitigation strategies (Rajesh, Ravi, & Venkata Rao, 2014), or for ranking agility enablers in a manufacturing environment (Aravind Raj, Sudheer, Vinodh, & Anand, 2013). The calculation of matrix permanent represents a four-step procedure and includes the following: i) identifying the vertices, which in case of RaSTs represent buyer, supplier, and customer; ii) defining the directions and weights of the edges, which in case of RaSTs reflect the types of the dyadic relationships between buyers, suppliers and customers in a service triad; iii) calculating the adjacency matrix permanent and the RIs associated with the specific types of RaSTs (see Appendix 6 for more details on calculating matrix permanent); and iv) comparing the calculated indices for ranking purposes[9].

[9] For additional information we suggest referring to the literature on measuring matrix permanent for matrices with unlimited number of nodes (e.g., Glynn, 2010).

3. When defining the RaSTs, we posit that no vertex contains internal risk(s) that constitutes a *self-loop*. Therefore, the diagonal of the adjacency matrices for the RaSTs in all three groups should constitute an array of 0s. Nevertheless, in order to avoid 0 values for RIs, especially for Group 1 of RaSTs where: $\forall i \in I = \{1, \dots, 12\}, per\ (A_i) = 0$ (see Appendix 6), we posit that the gradient of matrix for all weighted graphs extracted subsequently in our empirical study is 1 instead of 0. Accordingly, if we define a value range of 1-10 for all the other arrays of RaSTs according to their adjacency matrices, the maximum RIs for the triads in Groups 1, 2, and 3 are going to be 101, 1101, and 1201 respectively. These values for RIs indicate the extent to which a triad is exposed to risk.

Justification of RaST typology and an illustrative example of its use

To date, there have been no attempts in the literature to view and categorize the relational properties of the supply chain service triads from the point of view of their contribution towards the risk profile of the supply chain triad, seen as a system of interrelated supply chain partners. Below we adopt our RaST typology to categories the knowledge on the emerging risks within different types of supply chain service triads.

In Table 4.1, we categorize the buyer-supplier-customer RaSTs explored in the research literature according to the proposed typology of RaSTs. In some cases (e.g., Niranjan & Metri, 2008b), despite the fact that the service triads and their associated risks represent the core unit of analysis, only dyadic risks have been identified and no further investigation was conducted to analyse their impact on the adjacent dyads. In such cases, we used logical deduction to identify the adverse effects of these risks and to assign them to a particular RaST.

Though the number of studies investigating the buyer-supplier-customer triadic relationships is still limited, it can be concluded from the main groupings of Table 4.1 that certain types of triads in the proposed groups of RaSTs have attracted more interest from researchers than others. In particular, this relates to the first two groups, and especially RaST Type 8. This RaST type mainly deals with risks imposed by supplier on customer by the quality of the services provided and leading to the deterioration of the level of customer satisfaction (e.g., Finne & Holmström, 2013; Niranjan & Metri, 2008b). Such negative effect may potentially propagate into the relationship between the customer and the buyer who acts as an intermediary party. In some cases, similar to the bridge solidification scenario (Li, 2011; Li & Choi, 2009b), the strengthening of the ties in the supplier-customer dyad has detrimental impact on buyer-customer relations overtime. It is also posited that the aforementioned risks do not affect buyer-supplier relations or else they would be categorized in Group 3 and more specifically Type 27.

In summary, the result of the mapping reported in Table 4.1 reveals that the classification properties of the proposed RaST typology are sufficient to depict the examples of buyer-supplier-customer service triads and their associated risks reported in the literature. Moreover, the outcomes presented in Table 4.1 clearly indicate that a significant number of types of RaSTs specified in the reported typology (e.g., Group 3) have not yet been addressed in the research literature.

Table 4.1 Review of recent articles on buyer-supplier-customer service triads through the prism of RaST typology

Article	Risk Trigger(s) (Dyad)	Risk Taker(s) (Dyad)	Risk Neutral	RaST Type
Niranjan and Metri (2008b)	Service quality gap between client and customer *(Buyer-Customer)*	Lack of harmony between customer expectations and the received services by buyer *(Supplier-Customer/ Customer-Supplier)*	*Buyer-Supplier*	Type 3
	Customer influence negatively affecting buyer's performance *(Customer-Supplier)*	Customer dissatisfaction *(Buyer-Customer/ Customer-Buyer)*	*Buyer-Supplier*	Type 7
	Legal/operational/relational risks between client and buyer *(Supplier-Buyer or Buyer-Supplier)*	Customer dissatisfaction *(Buyer-Customer/ Customer-Buyer)*	*Customer-Supplier*	Type 5 Type 6
Li and Choi (2009b) and Li (2011)	Solidification of bridge position by supplier *(Supplier-Customer)*	Deteriorating relationship between buyer and customer *(Buyer-Customer/ Customer-Buyer)*	*Buyer-Supplier*	Type 8

Article	Risk Trigger(s) (Dyad)	Risk Taker(s) (Dyad)	Risk Neutral	RaST Type
	1) Adversarial buyer-supplier relationship *(Buyer-Supplier)* 2) Solidification of bridge position by supplier *(Supplier-Customer)*	Deteriorating relationship between buyer and customer *(Buyer-Customer/ Customer-Buyer)*	-	Type 17
	Deteriorating relationship between customer and buyer and bridge transfer *(Customer-Buyer)*	Having the advantage of critical information by supplier *(Supplier-Buyer/ Buyer-Supplier)*	*Supplier-Customer*	Type 9
	Reduction in the quality of services *(Supplier-Customer)*	Customer dissatisfaction *(Buyer-Customer/ Customer-Buyer)*	*Buyer-Supplier*	Type 8
	Supplier's appropriation behaviour *(Supplier-Buyer)*	Deteriorating relationship between customer and buyer and bridge transfer *(Buyer-Customer/ Customer-Buyer)*	*Supplier-Customer*	Type 5
van der Valk and van Iwaarden (2011) and van Iwaarden and van der Valk (2013)	Inappropriate behaviour of suppliers towards customers *(Supplier-Customer)*	Customer dissatisfaction *(Buyer-Customer/ Customer-Buyer)*	*Buyer-Supplier*	Type 8
	Conflicting objectives between: *1) Buyer-Supplier* *2) Customer-Supplier*	Customer dissatisfaction *(Buyer-Customer/ Customer-Buyer)*	-	Type 18
	1) Too much monitoring of supplier by customer *(Buyer-Supplier)* 2) Negative reaction of supplier on customer *(Supplier-Customer)*	Customer dissatisfaction *(Buyer-Customer/ Customer-Buyer)*	-	Type 17
Finne and Holmström (2013)	Suppliers lacking expertise in maintaining buyer's products for the customers *(Supplier-Customer)*	Increased downtime and higher maintenance costs of the customers *(Buyer-Customer/ Customer-Buyer)*	*Buyer-Supplier*	Type 8
Zhang, Lawrence, and Anderson (2015)	Conflicting goals between buyer and supplier (buyer pursuing brand equity while supplier aims at maximizing returns) *(Supplier-Buyer or Buyer-Supplier)*	Supplier increasing costs or decreasing the quality of services to maximize returns, resulting into customer dissatisfaction of buyer's brand *(Buyer-Customer/ Customer-Buyer)*	*Customer-Supplier*	Type 5 Type 6

Article	Risk Trigger(s) (Dyad)	Risk Taker(s) (Dyad)	Risk Neutral	RaST Type
Wuyts et al. (2015) and Modi, Wiles, and Mishra (2015)	Customers dissatisfied by the quality of services provided by the supplier *(Supplier-Customer)*	Developing an unfavourable perception of buyer and possibly terminating relationships with the buyer *(Buyer-Customer/ Customer-Buyer)*	*Buyer-Supplier*	Type 8

We illustrate the proposed typology of buyer-supplier-customer RaSTs by using it in the context of a service network comprised of a buyer, two customers and a supplier. It should be noted that the proposed approach based on RaST typology can be adopted in of more complex supply networks, which include more than three actors. An example is the quadratic risk-aware relationships in a buyer-supplier-customer 1-customer 2 network presented in Figure 4.4.

Figure 4.4 Quadratic risk-aware structure of buyer-supplier-customer relationships

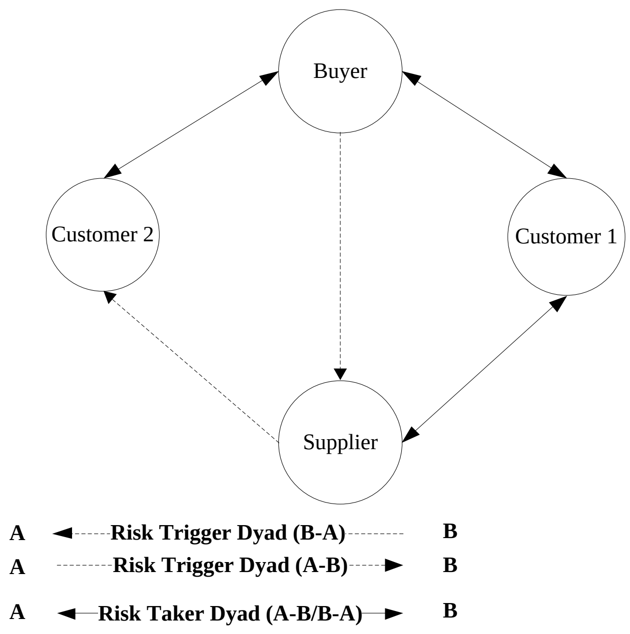


Figure 4.4 is illustrative of any simple service supply network in which the buyer has outsourced certain services to a supplier that simultaneously provides services to multiple customers. While fundamentally the nature of the two triads is the same (buyer-supplier-customer triad), it is only logical to assume that the risks and the severity of the disruptions that might occur in different triads of this network (i.e., buyer-supplier-customer 1 and buyer-supplier-customer 2) could differ. The two triads forming the quadratic network in Figure 4 have unique RIs and Nodal-in degree/Nodal-out degree values. In the first triad, on the right, one risk trigger dyad (i.e., buyer-supplier) and two risk taker dyads (i.e., buyer-customer 1 and supplier-customer 1) are presented, matching RaST type 29 in Figure 4.3. Depending on the values for risk trigger and risk taker dyads and using the formula in Appendix 6 and the adjacency matrix for this type of RaST in Figure 4.3, the permanent of this matrix could be calculated as the RI of this specific triad. The second triad on the left shows two risk trigger dyads (i.e., buyer-supplier, supplier-customer 2), and a risk taker dyad (i.e., customer 2-buyer), which matches RaST type 17 in Figure 4.2. Similar to the other triad in this network, RI of this triad could be calculated by assigning values to the risk exposures and possible disruptions occurring in the risk trigger and risk taker dyads. Next, by comparing the RIs, the triad characterized by a higher exposure to risk (i.e., a higher RI score) could receive a higher priority as part of the risk response and mitigation phase of the risk management process. As per the earlier comment, the suggested RaST-based approach to risk assessment is generalizable to more complex supply networks than the one described for illustrative purposes in this section.

Conclusions and future research

This study proposes and justifies a novel typology of the risk-aware buyer-supplier-customer service triads. The development of the typology has been guided by the design science research approach and the graph theory used as a modelling methodology formalizing the structural and relational properties of different types of Risk-aware Service Triads (RaSTs). Each individual RaST model forming the suggested typology is built on a unique set of characteristics (technological rules) outlining the mechanism of risk emergence and propagation among dyadic structures within each buyer-supplier-customer service triad. Specifically, the dyadic components of the service triads were classified according to their active, passive or neutral role in risk emergence and propagation within RaSTs. The categorization of these components and their formal representation using the graph theoretical approach resulted in thirty distinct types of RaST models, categorized in three groups.

The application of the graph theory allowed calculating the Risk Index (RI) as an implicit quantitative measure of risk, in line with the structural and relational properties of the underlying dyadic structures informed by the RaST typology. The suggested approach provides a quick and intuitive tool for risk assessment and ranking of RaSTs in line with their type and group within the RaST typology. It should be noted though that the application of this approach should not be regarded as the end point in the assessment of risks in service supply networks, but rather as a means to identify the critical areas (triads) and to timely allocate resources needed to address high risk exposures. Hence, based on the problem context, the risk assessment approach formulated in this study still requires to further conduct more context-specific analyses into the risk factors and vulnerabilities that shape risk exposures of the supply network (or its individual components) under consideration.

By presenting the RaST typology, the study focuses explicitly on risks triggered by the link-level properties (Bellamy & Basole, 2013) of the service triads. However, the vertex-specific risks triggered by the distinct members of the triads as well as the risks external to the service triads, that may affect the dyadic relations and the triad as a whole, have not been included in the proposed RaST typology. In the real-world situations, such assumption does not hold and the vertices, in addition to edges, could play a major role as risk triggers within a service triad. Having said this, the arrays of the gradient would have distinct numerical values other than non-zero values that are posited in the calculation phase. Furthermore, in conducting of real-world evaluations of risk exposures in service triads and to achieve more accurate scores of the resulting RIs, we recommend triangulating the managerial judgments about the severity of the risk exposures associated with the given processes from different sources including observations, historical loss data and semi-structured interviews (Barratt, Choi, & Li, 2011).

The output of this study calls for a wider application of graph theory for the analysis of risks in the context of cross-organizational collaborative relationships, including the buyer-supplier-supplier triads (e.g., Choi et al., 2002) and/or buyer-buyer-supplier triads (e.g., Choi & Kim, 2008). To further progress the ideas discussed in this chapter, our future research directions include an empirical evaluation of the proposed RaST typology via a series of case studies.

4.3. Paper 8: The application of graph theory for vulnerability assessment in service triads[10]

To determine the overall vulnerability of the triad to disruptive events and following the guidelines of the systems theory, service triads are conceptualized as complex adaptive systems that can be analysed at a variety of levels, including: individual organizations making up supply chain triads, supply chain dyads, and the overall systems level (the level of supply chain triads). Drawing on the growing literature on service triads, the present study aims to identify different cross-organizational pathways according to which risks can emerge and propagate within service triads, and to design the analytical model, which would facilitate quantification of vulnerability in service triads according to the aforementioned cross-organizational pathways of risk emergence and propagation. The applicability of the suggested approach to modelling and vulnerability assessment in supply chain service triads is illustrated in the service industry (corporate bond issuance) context. Using graph theory, a range of service triad reference models are developed, which formalize the typology and direction of the relationships between the members of the supply chain triad. Adopting the notion of matrix permanent allows calculating the vulnerability levels of distinct service triad models, accounting for the formalized typology and direction of the relationships within the models. A case study in a corporate bonds context is conducted to illustrate the applicability of the proposed approach to vulnerability assessment in the service industry context.

Keywords: service triad, supply network, vulnerability, disruption, graph theory, corporate bonds network

Introduction

Globalization and the recent technological advancements coupled with the need to cut costs and gain competitive advantage in volatile global markets have resulted in an ever-

[10] Pournader, M., & Rotaru, K. The Application of Graph Theory for Vulnerability Assessment in Service Triads. *Journal of Operational Research Society (Rank A).* (Under review).

increasing vulnerability of supply networks to disruptions (Ambulkar et al., 2015; Vilko & Hallikas, 2012). In the context of service sector, this growing vulnerability is a product of increased outsourcing activities rather than vertical integration practiced by firms in service supply networks (Hayes, 2008; Holcomb & Hitt, 2007). In view of the growing complexity of modern, highly diversified supply chains, it becomes apparent that the traditional focus on supply chain dyads needs to be extended in order to reflect the network nature of the modern supply chains (Carter et al., 2015; Mena et al., 2013; Wu et al., 2010). To provide a more realistic account of the network structure and inherent characteristics of the modern supply chains, a number of studies suggested shifting the analytical focus from supply chain dyads to triads seen as the elementary form of supply networks (Choi & Wu, 2009a; Niranjan & Metri, 2008a). The modelling focus on triadic relationships in supply chains allows to account for the interrelations between two supply chain members and the effect their interactions have on the third member, thereby capturing specific properties of network behaviour at the most elementary level of the supply network (Choi & Wu, 2009a).

The literature has distinguished a number of common types of supply chain triads, including: *buyer-supplier-customer* (e.g., Li & Choi, 2009c; Niranjan & Metri, 2008a; Rossetti & Choi, 2005a; Rossetti & Choi, 2008), *buyer-supplier-supplier* (e.g., Choi & Wu, 2009b; Choi et al., 2002; Dubois & Fredriksson, 2008; Wilhelm, 2011; Wu & Choi, 2005; Wu et al., 2010), and *buyer-buyer-supplier* (e.g., Choi & Kim, 2008). Early literature on supply chain triads predominantly considered the manufacturing context in which supply chain triads operate (e.g., Choi & Hong, 2002; Rossetti & Choi, 2005a), while up to date the context of service industries has received considerably less attention from the studies investigating supply chain triads (e.g., Bastl, Johnson, Lightfoot, & Evans, 2012). Our study addresses this research gap focusing specifically on supply chain triads that support the service outsourcing processes (e.g., Niranjan & Metri, 2008; Li & Choi, 2009; van der Valk & van Iwaarden, 2011; Perdikaki et al., 2015).

The focus of this study is on formal categorization of service supply network risks, including risks causing failure in service outsourcing practices, which aligns the structural and relational properties of risks reported in the service supply chain literature (Bastl et al., 2013; Choi, Wallace, & Wang, 2016; Perdikaki et al., 2015; Wuyts et al.,

2015) into a coherent framework grounded in graph theory (e.g., Bollobás, 1998). The latter allows to schematically represent the factors influencing major service supply chain disruptions and to suggest an analytical approach for vulnerability assessment of supply networks based on the notion of matrix permanent. To date no theoretically grounded approaches have been suggested to support reasoning about the potential risk scenarios associated with service triads. The literature has not yet structured the potential vulnerabilities that associated with relational properties between the members of supply chain triads and has not provided a structured analytical approach towards the assessment of such vulnerabilities. To address this research gap, we propose to use the modelling apparatus of graph theory, a mathematical approach widely adopted in operational research (e.g., Ahmadi-Javid, Ardestani-Jaafari, Foulds, Hojabri, & Farahani, 2015; Li, Kilgour, & Hipel, 2005; Ng, Cheng, Bandalouski, Kovalyov, & Lam, 2014).

Thus, the aim of this study is two-fold: (i) using the toolset of graph theory, to model different cross-organizational pathways according to which risks can emerge and propagate in service triads seen as an elementary form of service supply networks; and (ii) to provide a method for vulnerability assessment of the suggested graph models of service triads, taking into consideration the typology and direction of the cross-organizational relationships within graph models of supply chain triads. The applicability of the suggested approach to modelling and vulnerability assessment in supply chain service triads is illustrated in the service industry (corporate bond issuance) context.

The remainder of this paper is organized as follows: based on the body of literature outlined in the next section (*Background*), we identify the pathways of emergence and propagation of risk events that lead to disruptions in service triads. We then build an analytical model grounded in the graph theory to quantify vulnerability in service triads. This is followed by a case study in the context of corporate bonds issuance in Iran, which is conducted to demonstrate the practical application of the proposed analytical approach. We eventually provide the concluding remarks and further implications for research on evaluating vulnerability in service triads and service networks by incorporating the risk attitudes of decision makers as well.

Background

Risks and vulnerability of service triads

The emerging theory of the supply chain (Carter et al. (2015) grounded in the systems theory (e.g., Simon, 1996) and network theory (e.g., Wasserman & Faust, 1994), conceptualizes supply chains as: (a) networks consisting of focal organizations that are linked to upstream and downstream partners; and (b) complex adaptive systems, which exhibit such properties as self-organization, emergence and limited visibility of individual partners. This view suggests that all members of a supply chain can be viewed as self-organizing adaptive agents that are interconnected in such a manner that the behaviour of one agent commonly affects the behaviour of the whole system (Choi & Hong, 2002; Nair et al., 2009). In today's dynamic and highly interconnected environment, supply chain risks, and specifically supply chain disruptions, are commonly considered as natural, or 'normal' (i.e., using the language of the normal accident theory), properties of the modern supply chains (Marley et al., 2014). From the point of view of the emerging theory of the supply chain, such risks represent emergent properties of the service supply network structures (Carter et al., 2015). However, in view of the high level of interconnectedness between the members of the supply chain networks and lower levels of control (as compared to the vertically integrated supply chains), the risks of supply chain disruptions represent a particular concern due to their high impact and the ability to carry across the organizational boundaries the adverse effects of such events (Lodree Jr & Taskin, 2008). The recent examples in the literature include the propagation of the detrimental effects of such events as bankruptcy (Garvey et al., 2015) and as terrorist attacks (Bueno-Solano & Cedillo-Campos, 2014) across the members of the supply chain network.

The enhanced ability to respond to changes in demand and benefit from the associated business opportunities often goes hand in hand with the increasing dependency on quantum of work outsourced by service companies to their suppliers The latter leads to an extension of the supply chains both in size and complexity (Ellram et al., 2008; Harland, Brenchley, & Walker, 2003; Tate, Ellram, & Brown, 2009a). In addition, along with the increasing profit margins and other performance improvement outcomes achieved through the growing complexity and dynamism of the modern supply networks, comes the issue of the increased vulnerability of the supply networks and their individual members (Choi, Wallace, et al., 2016; Sodhi & Tang, 2012b; Wagner & Bode, 2008). Service companies seek to establish proper relationships with members participating in the outsourcing practices and consider such relationships as key for achieving a desirable level of services delivered (Bastl, Johnson, Lightfoot, & Evans, 2012b; Pawar, Beltagui, & Riedel, 2009). Given the importance of such relationships, the companies today are urged to establish additional forms of disruption response strategies and control procedures as part of their profiles to avoid new disruptions including adversarial buyer-supplier relations or winning customers over by suppliers, to name a few (Choi & Kim, 2008; Li & Choi, 2009c).

In one of the early studies investigating service triads, Li and Choi (2009c) adopted the social network lens to highlight an emerging condition, referred to as *structural holes* (Burt, 1992), which differentiates *buyer-supplier-customer* triads in service industries from other business contexts, such as manufacturing. For instance, while in manufacturing the role of the buyer as a bridge between supplier and the buyer's customer remains stable, in the service industries this relationship is more dynamic and is typically the function of time relative to the outsourcing of specific services. At the negotiation stage, the buyer maintains the bridge position, which however starts to decay during outsourcing when the supplier gets into the direct contact with the buyer. This may then lead to the bridge transfer phase when the customer may find it more comfortable working directly with the supplier without the buyer serving as intermediary in this triadic relationship. This transition from the bridge to the bridge decay position reflects the loss of control by the buyer upon the communication channel between the supplier and the customer and results in the redistribution of relational benefits originally shared by members of the supply chain triad to the members of the newly formed dyadic business model.

Another example is the study by Niranjan and Metri (2008a) who considered the relational properties in *client-vendor-consumer service triads,* outlined the factors that lead to quality erosion in this triadic relational model and discussed the tensions between business-to-business and business-to-customer dimensions forming this triadic relationship. (van der Valk and van Iwaarden (2011)) focused on *buyer-subcontractor-end customer* triads and the supervisory attempts that contribute to the development of more robust contracts for services outsourcing purposes. This problem is further discussed by (van Iwaarden and van der Valk (2013)) who used a case-based approach to demonstrate how the service delivery process can be controlled at the early stages by devising control mechanisms in the associated service level agreements.

More recently, based on the analysis of archival data from Compustat database, Kim and Henderson (2015) demonstrated the unequivocal nature of supplier and customer benefits with an increasing dependency upon focal firm in concentrated triadic relationships: the economic benefits of customer dependency diminish beyond a certain point, while those of supplier dependency continue to increase above that threshold. Modi et al. (2015) used the event study methodology to investigated 146 cases of security breaches as part of the pioneering investigation of the effects of service failures due to service provider in the context of service outsourcing triads. Summarizing the above, vulnerability in the context of service triads may result from the weakness or threat brought by one member of the supply chain triad or as a relational property of two members of the supply chain triad.

Finally, Wynstra et al. (2015) continued the investigation into the various configurations of buyer-supplier-customer triads, outlining the theoretical approaches supporting the conceptualization of the notion of triads, describing a number of distinctive properties of service triads, and broadening the perspectives for future research in this growing body of operations and supply chain management literature. Their study is probably the most complete literature review of the published research on supply chain triads in both service and manufacturing sectors. Neither of the prior studies reviewed by Wynstra et al. (2015) investigated risk as a phenomenon which characterize the relationships between the members of the supply chain triads in services or manufacturing. Naturally, the mechanisms that shape and transform the relationships between the members of the supply chain triads (such as, for example, bridge, bridge decay, and bridge transfer mechanisms suggested by Li and Choi (2009c)) relate to the emergence of risky scenarios in triads (e.g., buyer losing control at a bridge decay stage and ultimately leaving the business model when the bridge transfer takes place). However, the studies that did contribute to the improved understanding of the drivers of risk within supply chain triads did not consider the phenomenon of risk per se as the object of their investigation.

Service triads as complex adaptive systems

A considerable amount of risks threatening the continuity of operations in supply networks, including service supply networks and their individual service triads, are context-specific. Such risk events largely depend on the nature of operational processes and inbuilt controls of organizations forming supply networks, as well as the characteristics of external environment in which they operate (Lewis, 2003; Neiger et al., 2009; Tan, Lee, & Goh, 2012). Moreover, both emergence of these risks and their propagation across organizational boundaries are closely associated with the properties of the supply networks (Carter et al., 2015), and specifically service triads, and the nature of the relationships between its members (Mizgier, Jüttner, & Wagner, 2012). Some of the core properties of supply networks through the lens of network theory and complex adaptive systems are outlined below.

According to the principles of *network theory*, a triad is defined by Wasserman and Faust (1994, p. 19) as “a subset of three actors and the (possible) tie(s) among them”. A service triad is commonly regarded as an independent elementary form of a service supply network and shares certain structural and behavioural characteristics of the network (Havila, Johanson, & Thilenius, 2004; Niranjan & Metri, 2008a). The term 'possible tie(s)' used in Wasserman’s (1994) definition of triads, implies up to six different types of triads built on a continuum of inter-organizational relationships from less to more connected members (for more details, see Peng, Lin, Martinez, & Yu, 2010b). For the study of service triads, an extension to the original six types of triads is considered, with the aim of taking into account all three bipartite relationships of service triad members in order to determine the possible pathways of emergence and propagation of risks that may lead to disruptions within the service triad.

One of the distinctive characteristics of supply networks, as seen from this theoretical perspective, is the notion of *emergence*: "the rising of new, unexpected structures, patterns, properties, or processes in a self-organizing system" (Choi et al., 2001, p. 354). This notion is grounded in *systems theory* (Daellenbach, 1994; Simon, 1996) and in the later literature on *complex adaptive systems* (Choi & Hong, 2002; Nair et al., 2009). From the systems perspective, a service triad as an elementary form of a service supply network possesses the characteristics of a complex adaptive system whose "behavior ... is induced not by a single entity but rather by the simultaneous and parallel actions of agents within the system itself" (Choi et al., 2001, p. 354). Thus, a service triad exhibits unique characteristics, or emergent properties, which are not properties of its distinct components but the whole network. Along with drivers of value creation in supply chain triads, risks associated with the design and functioning of the service triads represent properties pertinent to the triadic system where they emerge. One of the innate characteristics of such risks is their ability to propagate across the boundaries of individual organizations forming the triad (Garvey et al., 2015). For example, among other disruptive events or states, the literature reports on the propagation of the adverse effects produced by terrorist acts (Bueno-Solano & Cedillo-Campos, 2014) and bankruptcies (Garvey et al., 2015) across inter-organizational boundaries within supply chain triads. .

To date, the literature investigating the issues of disruption modelling and vulnerability assessment in the context of service triads is still scarce. The need to account for the interactions among all members when conducting vulnerability assessment of service triads makes it problematic to directly adopt the formal approaches to vulnerability assessment commonly applied to individual organizations or dyadic cross-organizational relationships. We address this research gap by adopting a graph theory analytical approach to model disruptions and assess vulnerability in service triads. In the next section the relevant analytical model is presented.

Analytical model

Graph theory

The versatility of graphs in modelling the relationships between members of networks has made it widely applicable in social, technological, informational and biological networks (Borgatti & Halgin, 2011; Borgatti & Li, 2009; Newman, 2003; Wasserman & Faust, 1994). Graph theory provides the analytical means to study diverse types of relations (i.e., edges) between a set of entities (i.e., vertices) in an environment characterized by the relationship between two and more entities (Bollobás, 1998). A graph $G = (V, E)$ consists of a set of vertices $V_G = \{v_1, v_2, \dots\}$ and a set of edges $E_G = \{e_1, e_2, \dots\}$ where each edge is defined by a pair of vertices. Each vertex in graphs may represent a property of a system or an entity which makes part of the system being modelled, while edges commonly reflect the relational properties between the vertices and commonly reflect such notions as flows of material, information, finance, and others, when modelling the relationships between such agents as companies and individuals (Bondy & Murty, 1976; West, 1996). The ability of graphs to model a wide range of relationships and flows between different agents in a given context makes graphs an appropriate tool for modelling various flows of information, goods, services type of supply chain networks, including service supply chain networks, and service triads as their elementary form.

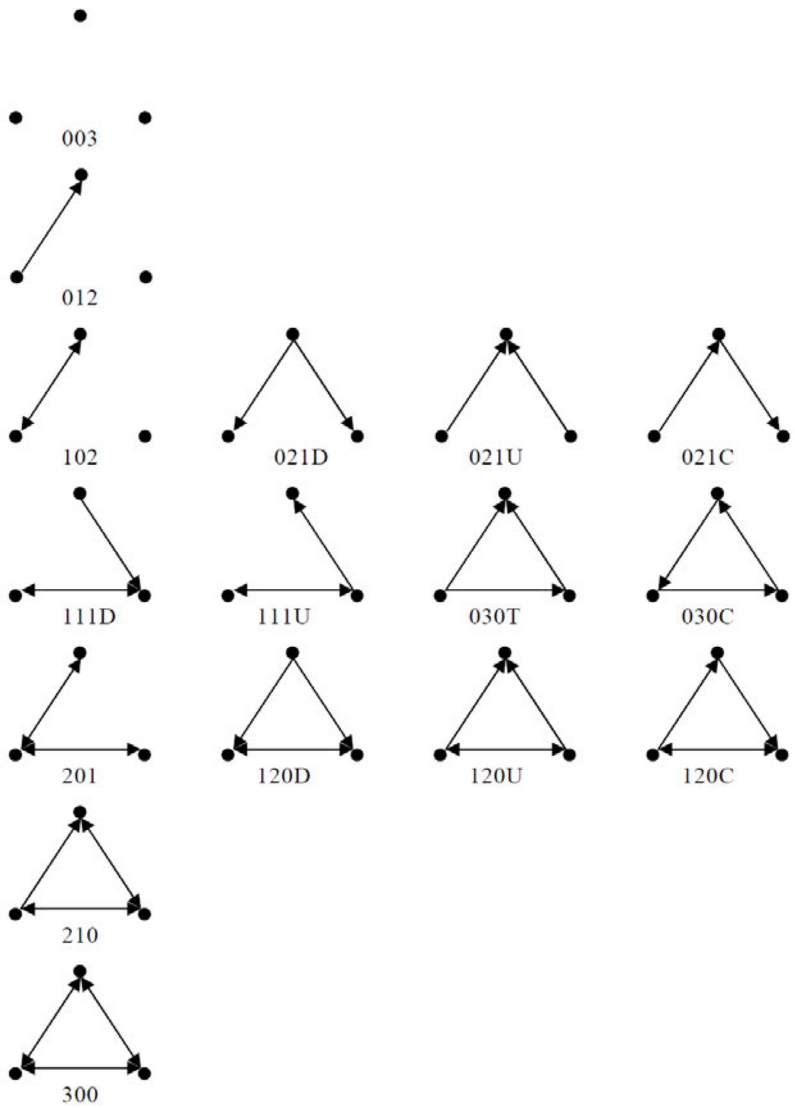
Graphs have been for long used to model interdependencies in triadic structures and more complex social networks (e.g., Davis, 1967; Harary, 1965; Holland & Leinhardt, 1970), however their application to modelling the supply chain triads and their properties has been very limited. In their review of the studies adopting network analysis approaches to investigate supply chains, Borgatti and Li (2009) distinguish a number of promising research directions among which is the application of the graph theoretical approach to model the network structure and relevant properties of supply chains. To have a better understanding of existing vulnerabilities and the level of resilience to potential disruptions in supply networks, Kim et al. (2015) suggest the application of graphs to differentiate between disruptions on the node level (i.e., disruptions in internal processes of firms) and on the dyadic level (i.e., disruptions in the interrelations between each pair of firms).

A graph theoretical approach for vulnerability assessment in service triads

A *directed graph* (digraph) represent a set of interconnected nodes where the edges are directed from one node to another. When applying digraphs for vulnerability assessment in service triads, the members of a service triad are presented as vertices of the graph and the direction of the edge between each member shows the direction of risk imposed from one member to another at the end of the edge arrow. Assigned weights to the directed edges in such graphs show the severity of disruptions occurring between the bipartite members. Thus, directed weighted edges are used as indicators of direction and magnitude of potential disruptive events occurring between any two members of a service triad (i.e., between each pair of vertices).

Figure 4.5 shows all the possible configurations of triads in a network (Holland & Leinhardt, 1970). In the context of this study, a unidirectional arrow between vertex A and vertex B ($A \rightarrow B$) shows that A is imposing disruptions to the processes of B (asymmetric relationship). A two directional arrow ($A \leftrightarrow B$) shows both A and B disrupting each other's processes (mutual relationship). Also, no arrow indicates no disruption between A and B (null relationship). The triads are labelled in accordance with the number of mutual (M), asymmetric (A), and null (N) pairs in each triad, defined as *MAN* labelling. For instance, triad 102 shows that there is one mutual (i.e., disruption directed from both vertices), no asymmetric, and two null pairs of relationships in the triad. Or label 003 shows a disruption-free service triad with no mutual, no asymmetric and three null pairs. The letters are also used to further distinguish between the triads (*D* for *Down*, *U* for *Up*, *T* for transitive, and *C* for *Cycle*). However, the sixteen different types of triads proposed by Holland and Leinhardt (1970) are tailored for triads with identical members. For a triad with non-identical members (e.g., buyer-supplier-customer triad, buyer-supplier1-supplier2 triad, etc.) the total number of variations for the triads that conceptualize disruptions equals to $3! \times 16 = 96$ different configurations. Identifying the types of triads as presented in Figure 4.5, helps network analysts to test their hypotheses on the structural properties of the networks such as *transitivity* and *intransitivity* (Faust, 2006; Wasserman & Faust, 1994), which provides interesting avenues for future research in the context of both manufacturing and service triads in operations management. Using the configurations presented in this section, we aim to model service triads and quantify their vulnerability levels depending on the nature of the relationships between their members.

Figure 4.5 Different configurations of triads using MAN labelling (referring to mutual (M), asymmetric (A), and null (N) pairs in each triad)



Some of the configurations of the triads presented in Figure 4.5 have been discussed in the literature on triads and service triads. For example, 021U corresponds to the so called *structural holes* (Burt, 1992, 2005) and the *bridge*, *bridge decay, bridge transfer* characteristics of service triads described by Li and Choi (2009c), where the supplier tries to solidify its bridge position by making stronger ties with the customer and by disrupting the relationship between the customer and the buyer (Supplier→Buyer and Customer→Buyer) by luring away the customer. Specifically, the triad type 012 reflects a disruption in the buyer-customer relationship (Customer→Buyer) in the *bridge transfer* stage but no disruption in buyer-supplier or supplier-customer relationship. Zhang et al. (2015) highlight conflicts between buyer (i.e., the main service provider outsourcing services to a third party supplier) and supplier, which results in increased costs of services (Supplier→Customer) and customers being unhappy with both supplier (Customer→Supplier) and buyer (Customer→Buyer). This scenario reflects the triad type 111U.

Despite the evidence presented above, a vast majority of possible configurations of disruptions emerging and propagating in service triads have yet to be identified and addressed in the published service triad models. Moreover, in almost all the aforementioned instances vulnerabilities associated with the internal processes of the firms forming service triads as well as their adverse effect on triads were not considered. Furthermore, the focus of the literature that investigates the risks of supply chain disruptions is still largely on the disruption events themselves, while the propagation of the adverse effects of such events across the boundaries of individual organizations largely remains outside the scope of the research studies. For instance, what are the next steps in the outsourcing case by Li and Choi (2009c) after the bridge transfer phase when the buyer realizes that the supplier had lured the customer away? Would the relationship between buyer and supplier be disrupted? How it might impact the whole supply network? Moreover, after identifying the type of triad that represents correctly disruptions between its members, how could the overall vulnerability of the triad be assessed? To address the questions above, first we introduce *matrix permanent* as a tool used to conduct vulnerability assessment in supply service triads and more complex supply networks.

Matrix permanent and its application in service triads

To assess how the proposed graph models could help assessing vulnerabilities to disruptions in service triads, we use the notion of *matrix permanent*, which originates in multi-linear algebra and combinatorics (Marcus & Minc, 1965; Ryser, 1963). For instance, the permanent of a 0,1 matrix representing a bipartite graph is the number of perfect matchings in the graph. Permanents have been already used in different operational contexts as indicators of cost effectiveness (Sabharwal & Garg, 2013), effectiveness of risk mitigation strategies (Rajesh et al., 2014), ranking agility enablers in a manufacturing environment (Aravind Raj et al., 2013), and others. The same approach has been adopted by Wagner and Neshat (2010) and Wagner and Neshat (2012) to calculate vulnerabilities of supply chains to different types of supply chain risks. They considered vulnerability drivers as the vertices and their interdependencies as edges and by calculating the resultant matrix permanent, they introduced a quantified supply chain vulnerability index. Our model is different from the latter in that we simultaneously incorporate vulnerabilities observed both in the internal processes of triad members (representing diagonal elements) and in their interrelations with other members (representing off-diagonal elements) and its adverse effect on the triad's vulnerability as a whole.

Alternative methods are presented to calculate the permanent function of a matrix (Brualdi & Ryser, 1991; Glynn, 2010; Ryser, 1963). For the convenience of the computational procedure, in this study we follow Rao's (2007) work that expanded the permanent for the $M \times M$ matrix representation of digraph J (1) with the equation (2) as follows,

$$J = \begin{bmatrix} A_1 & a_{12} & \cdots & a_{1M} \\ a_{21} & A_2 & & a_{2M} \\ \vdots & & \ddots & \vdots \\ a_{M1} & a_{M2} & \cdots & A_M \end{bmatrix} \quad (1)$$

$$per\ (J) = \prod_{i=1}^{M} A_i + \sum_{i=1}^{M-1} \sum_{j=i+1}^{M} \cdots \sum_{M=t+1}^{M} \begin{matrix} (a_{ij}a_{ji}) A_k A_l A_m A_n A_o \ldots A_t A_M \\ \ldots, M \neq pus \end{matrix} \quad (2)$$

$$+\sum_{i=1}^{M-2}\sum_{j=i+1}^{M-1}\sum_{k=j+1}^{M}\overset{\cdots}{l=1}\sum_{M=t+1}^{M}\underset{k,\ldots,M\neq pus}{(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji})A_lA_mA_nA_o\ldots A_tA_M}$$

$$+\left[\begin{array}{l}\displaystyle\sum_{i=1}^{M-3}\sum_{j=i+1}^{M}\sum_{k=i+1}^{M-1}\sum_{l=i+2}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,\ldots,M\neq pus}{\big(a_{ij}a_{ji}\big)(a_{kl}a_{lk})A_mA_nA_o\ldots A_tA_M} \\ \displaystyle+\sum_{i=1}^{M-3}\sum_{j=i+1}^{M-1}\sum_{k=j+1}^{M}\sum_{l=j+1}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,\ldots,M\neq pus}{\big(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji}\big)A_mA_nA_o\ldots A_tA_M}\end{array}\right]$$

$$+\left[\begin{array}{l}\displaystyle\sum_{i=1}^{M-2}\sum_{j=i+1}^{M-1}\sum_{k=j+1}^{M}\sum_{l=1}^{M-1}\sum_{m=l+1}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,m,\ldots,M\neq pus}{\big(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji}\big)(a_{lm}a_{ml})A_nA_o\ldots A_tA_M} \\ \displaystyle+\sum_{i=1}^{M-4}\sum_{j=i+1}^{M-1}\sum_{k=i+1}^{M}\sum_{l=i+1}^{M}\sum_{m=j+1}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,m,\ldots,M\neq pus}{\big(a_{ij}a_{jk}a_{kl}a_{lm}a_{mi}+a_{im}a_{ml}a_{lk}a_{kj}a_{ji}\big)A_nA_o\ldots A_tA_M}\end{array}\right]$$

$$+\left[\begin{array}{l}\displaystyle\sum_{i=1}^{M-3}\sum_{j=i+1}^{M-1}\sum_{k=i+1}^{M}\sum_{l=j+1}^{M}\sum_{m=1}^{M-1}\sum_{n=m+1}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,m,n,\ldots,M\neq pus}{\big(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji}\big)(a_{mn}a_{nm})A_o\ldots A_tA_M} \\ \displaystyle+\sum_{i=1}^{M-5}\sum_{j=i+1}^{M-1}\sum_{k=j+1}^{M}\sum_{l=1}^{M-2}\sum_{m=l+1}^{M-1}\sum_{n=m+1}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,m,n,\ldots,M\neq pus}{\big(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji}\big)(a_{lm}a_{mn}a_{nl}+a_{ln}a_{nm}a_{ml})A_o\ldots A} \\ \displaystyle\quad+\sum_{i=1}^{M-5}\sum_{j=i+1}^{M}\sum_{k=i+1}^{M-3}\sum_{l=i+2}^{M}\sum_{m=k+1}^{M-1}\sum_{n=k+2}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,m,n,\ldots,M\neq pus}{\big(a_{ij}a_{ji}\big)(a_{kl}a_{kl})(a_{mn}a_{nm})A_o\ldots A_tA_M} \\ \displaystyle\sum_{i=1}^{M-5}\sum_{j=i+1}^{M-1}\sum_{k=i+1}^{M}\sum_{l=i+1}^{M}\sum_{m=i+1}^{M}\sum_{n=j+1}^{M}\cdots\sum_{M=t+1}^{M}\underset{k,l,m,n,\ldots,M\neq pus}{\big(a_{ij}a_{jk}a_{kl}a_{lm}a_{mn}a_{ni}+a_{in}a_{nm}a_{ml}a_{lk}a_{kj}a_{ji}\big)A_o\ldots A_tA_l}\end{array}\right]$$

$$+\cdots$$

where $a_{ij}, i, j = 1, \ldots, M$ denotes the relative value of attribute a_{ij}, which in our case is the relative vulnerability detected in the relationship between member i and member j within a triad. Also, $A_i, i = 1, \ldots, M$ is the absolute value for the ith attribute, which is interpreted as the measure of vulnerability to disruptions for each triad member in its internal processes to disruptions irrespective of its interrelations with other triad members. The acronym *pus* stands for *previously used subscripts*, which means that $k, l, m, \ldots, M$ take subscripts in (2) that are not previously used. There are overall $M + 1$

groups of terms in (2) with each group showing the relative importance measures of attributes in the digraph J. For instance, the first group shows the measures of M unconnected vulnerability attributes corresponding to internal vulnerabilities of members. The second group illustrates a bipartite vulnerability measure. Third group of terms shows the vulnerability between each set of three attributes and vulnerability measures of $M-2$ attributes, and so on.

Considering graph A ($V_A = \{A_1, A_2, A_3\}, E_A = \{a_{12}, a_{21}, a_{13}, a_{31}, a_{23}, a_{32}\}$) (representing a triad) and (2), permanent of graph A can be presented as follows,

$$per(A) = A_1A_2A_3 + (a_{12}a_{21}A_3 + a_{13}a_{31}A_2 + a_{23}a_{32}A_1) + (a_{12}a_{23}a_{31} + a_{13}a_{32}a_{21}) \quad (3)$$

Service supply networks with $n \geq 3$ vertices consist of $\binom{n}{3} = \frac{n!}{(n-3)!*3!}$ triads. Thus in order to capture the vulnerability level for the network, all different types of triadic models associated with potential disruption events should be considered and evaluated. Next, for the purposes of illustrating the use of the suggested modelling and vulnerability assessment approach using graphs, we consider the corporate bonds network with five vertices. In doing so, we show the measures that should be taken into account when assessing vulnerability in service supply networks, such as service triads.

Application of the analytical model

To test our proposed approach of identifying disruptions in service triads and quantifying the resultant vulnerabilities as the core elements of service supply networks, we conduct several case studies in the corporate bonds setting of Iran (financial industry service sector, according to the classification suggested by Wynstra et al. (2015)). In the next subsection we provide a brief overview of the corporate bonds market in Iran and describe the corporate bonds network, as well as the associated risks. We then present the cases and report on the results obtained from applying our proposed analytical approach informed by the graph theory to the corporate bonds service triads.

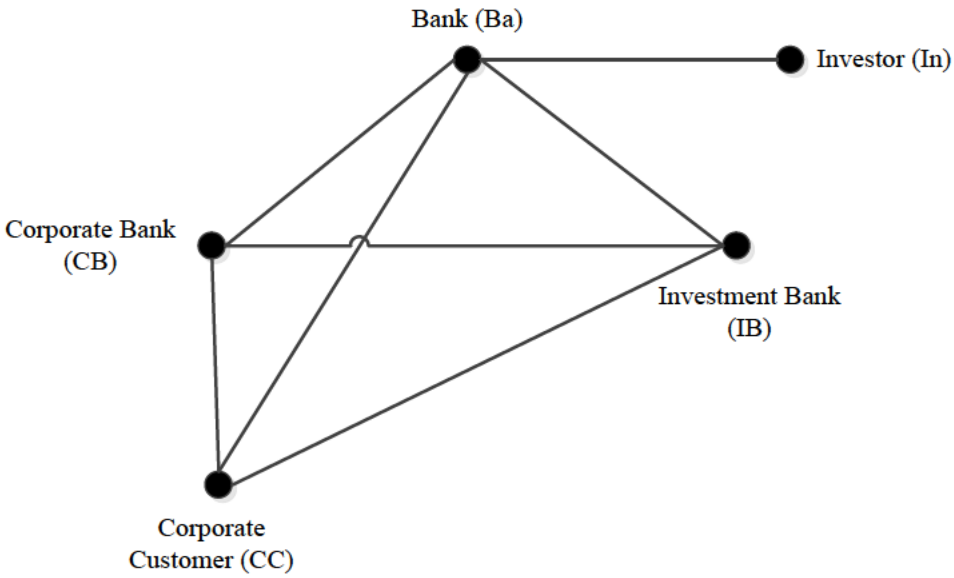
Corporate bonds network context

Corporate bonds for the last two decades have become one of the main tools to fund large corporations around the globe (Massa, Yasuda, & Zhang, 2013; Mizen & Tsoukas, 2012; Thomas, Oliver, & Hand, 2005). A simple corporate bonds network consists of corporate customers as *issuers*, a bank and its corporate bank or a bank and an external investment bank as *underwriters*, and *investors* who purchase the bonds. When deciding to issue bonds, the issuer refers to an underwriter to receive services such as pricing, marketing, documenting, and selling the bonds as well as insurance for the unsold bonds and other types of services (Yasuda, 2005, 2007). There have been numerous cases of fraud and disruptive behaviour reported in the context of corporate bonds network (see, Andres et al., 2014; Shivdasani & Song, 2011), leading to a stronger information asymmetry (Healy & Palepu, 2001), financial distress (Berlin, John, & Saunders, 1996), and realized default and credit risk (see among, Altman, 1989; Giesecke, Longstaff, Schaefer, & Strebulaev, 2011; Güntay & Hackbarth, 2010; He & Xiong, 2012; Krishnan, Ritchken, & Thomson, 2005; Vassalou & Xing, 2004) for the members of the network. In addition to the realized risks mentioned above that may potentially disrupt the continuity of the bipartite relations between the members of the corporate bonds network; each member may also experience disruptions within its own organizational processes that could propagate across the organizational boundaries and affect other members and on the triad as well. Our goal is to investigate the vulnerability of a given supply chain triad to these different levels of disruption in the context of corporate bonds service triads.

Case study: Corporate bonds service networks

The emerging nature of Iranian financial market and its fixed 20 percent coupon on corporate bonds offer significant investment opportunities (Lynn, 2014; Rao, 2014b). Since its inauguration in the 1990's, the turnover of the corporate and government bonds market has been assessed in billions of dollars per annum, according to the annual report of Central Bank of Iran. Especially after corporate banking was introduced to this financial market in 2007, corporate bonds market has become even more competitive with both investment banks and corporate banks aiming to gain a larger share of the market. Usually, in very large projects banks decide to use both their corporate bank and at least one external investment bank to collaborative on bond underwriting and issuance processes. To better understand the bottlenecks (i.e., most vulnerable service triads) of the corporate bonds network, we investigate networks comprised of corporate customers, banks and their corporate banks, investment banks, and investors (see Figure 4.6). Using semi-structured interviews, we investigate the emergence and propagation of disruptions in different service triads which form part of the Iranian corporate bonds service network. We then assess and compare vulnerability scores of the identified triads and discuss the results.

Figure 4.6 Corporate bonds network with five main members

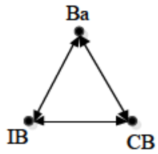
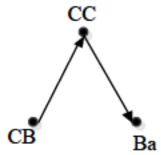
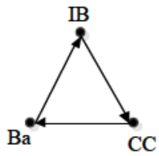


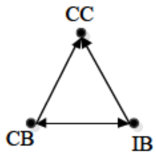
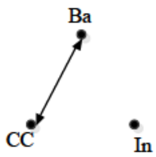
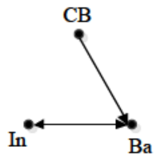
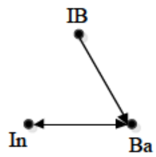
Our semi-structured interview process involved multiple stakeholders. We interviewed heads of four main banks and their corporate banks (i.e., Eghtesad Novin (EN) Bank, Mellat Bank, Melli Bank, and Saman Bank) along with four external investment banks (Amin, Novin, Omid, Sepehr) that cooperated with these banks to issue corporate bonds. We also interviewed a number of corporate customers for these banks that were involved in extensive bonds issuance and underwriting projects. Moreover, we interviewed representative groups of investors that were investing in the bonds issued by the above mentioned banks. Twenty-two interviews were conducted, including six interviews with bank and corporate bank representatives, eight interviews with the investment banks and four interviews with corporate customers and investors. The key informants included top- or high-level managers, mainly CEOs, CFOs or heads of relevant departments. The criterion for the selection of interviewees was their involvement in the process of issuing and underwriting corporate bonds (see Appendix 7 for the profile of the respondents). The names of the corporate customers are not disclosed in this study due to the confidentiality reasons. Moreover, pseudonyms are used to represent vertices in the corporate bonds network: Bank (Ba), Corporate Bank (CB), Investment Bank (IB), Corporate Customer (CC), Investor (In).

The interviews took place from December 2012 to April 2013 and were conducted either on site, with the interview time ranging from approximately one hour to three hours. Respondents were first asked to introduce themselves and talk about their responsibilities. Next, using a 10-point Likert scale we asked the interviewees to identify and assess types of disruptions in the internal processes of the organization they are associated with and its impact on the corporate bonds network they are part of (Question 02). Next, the critical incident technique (Gremler, 2004) was adopted to question the informants' opinions on the most significant adverse events and situations in their interactions with the other two members of the corporate bonds service triad. We then asked the participants to prioritize the impact of those adverse events using a 10-point Likert scale (Questions 03-06, see Appendix 8 for the interview protocol). Three investigators conducted the interviews in order to increase the confidence level of the research outcomes (Benbasat, Goldstein, & Mead, 1987b; Dubé & Paré, 2003).

Overall we investigated four different corporate bonds networks consisting of either one of the above-mentioned banks, their corporate banks, a unique external investment bank and their corporate customers and investors. Table 4.2 shows the results of the analysis of one of the four corporate bonds networks (i.e., Mellat corporate bonds network). According to Table 4.2, initially all possible forms of $\binom{5}{3} = 10$ service triads are identified. The graph representations of disruptions in these triads are visualized upon interviewees' comments on the severity of disruptions at vertex and dyad levels that could have affected the triads. The graph models are followed by the specification of the types of triads using MAN labelling and their matrices are presented. In the *Vulnerability score* column, the vulnerability level of each triad is quantified using equation (3). While each triad is attributed its own specific type of disruptions reported in Table 4.2, we consider some common types of vertex-level disruptions for the internal processes of the members such as *bureaucracy* and *obsolete IT systems* for the bank, investment bank and corporate bank, *financial instability* for the corporate customer, and *unwillingness to purchase the bonds (emergence of parallel markets with higher interest rates, increased* *risk of corporate bonds, etc.)* for investors. This is in line with the frequency of these disruptions mentioned by the interviewees. *Disruption(s) description* column shows disruptions on and dyad level.

Table 4.2 Graph models of disruption pathways and corresponding vulnerability scores in Mellat corporate bonds network

Triad type[1]	Disruption(s) description	Corresponding graph	Corresponding matrix (T_i)	Vulnerability score
IB-Ba-CB	Lack of coordination (Ba-CB and CB-Ba) Lack of coordination (Ba-IB and IB-Ba) Lack of coordination (IB-CB and CB-IB)	 3002[2]	$T_1 = \begin{matrix} IB \\ Ba \\ CB \end{matrix} \begin{bmatrix} 7 & 7 & 5 \\ 7 & 5 & 3 \\ 5 & 3 & 7 \end{bmatrix}$	986
CB-CC-Ba	Lack of skills and low experience (CB) Low quality of services (CB-CC) Dissatisfaction and mistrust (CC-Ba)	 021C	$T_2 = \begin{matrix} CB \\ CC \\ Ba \end{matrix} \begin{bmatrix} 9 & 5 & 0 \\ 0 & 3 & 3 \\ 0 & 0 & 5 \end{bmatrix}$	135
Ba-IB-CC	Insufficient supervision (Ba-IB) Opportunistic behaviour (IB-CC) Dissatisfaction and mistrust	 030C	$T_3 = \begin{matrix} Ba \\ IB \\ CC \end{matrix} \begin{bmatrix} 5 & 7 & 0 \\ 0 & 7 & 7 \\ 7 & 0 & 3 \end{bmatrix}$	448

	(CC-Ba)			
CB-CC-IB	Untimeliness and low quality of services (CB-CC) Untimeliness and low quality of services (IB-CC) Lack of coordination (IB-CB and CB-IB)	 120U	T_4 $\begin{matrix} CB \\ = CC \\ IB \end{matrix}\begin{bmatrix}7&5&5\\0&3&0\\5&3&7\end{bmatrix}$	222
CC-Ba-In	Lowering the price of bonds for marketing purposes and high commissions (Ba-CC) Financial loss and dissatisfaction of corporate customer (CC-Ba)	 102	T_5 $\begin{matrix} CC \\ = Ba \\ In \end{matrix}\begin{bmatrix}3&5&0\\3&5&0\\0&0&1\end{bmatrix}$	30
In-CB-Ba	Inaccuracy in credit check of issuing corporate and faulty pricing (CB-Ba) Providing false credit information and unrealistic prices to investors (Ba-In) Reputation loss (In-Ba)	 111D	T_6 $\begin{matrix} In \\ = CB \\ Ba \end{matrix}\begin{bmatrix}1&0&7\\0&7&9\\7&0&5\end{bmatrix}$	378
In-IB-Ba	Inaccuracy in credit check of issuing corporate and faulty pricing (IB-Ba) Providing false credit information and unrealistic prices to investors (Ba-In) Reputation loss (In-Ba)	 111D	T_7 $\begin{matrix} In \\ = IB \\ Ba \end{matrix}\begin{bmatrix}1&0&5\\0&7&5\\5&0&5\end{bmatrix}$	210

CB-In-IB	-	-	-	-
CC-In-IB	-	-	-	-
CC-In-CB	-	-	-	-

1 Ba (Bank), CB (Corporate Bank), CC (Corporate Customer), IB (Investment Bank), In (Investor)
2 MAN label

Looking at the vulnerability scores from Table 4.2, three most vulnerable service triads in the corporate bonds network #1 are IB-Ba-CB (T_1, score: 986), Ba-IB-CC (T_3, score: 448), and In-CB-Ba (T_6, score: 378). In the IB-Ba-CB triad, the main concerns of the interviewees were the lack of coordination between investment bank, bank and its corporate bank which might in turn lead to delays, decreased quality of services, and financial losses for all members of this triad. Participants, especially top executives of the bank, were concerned about the opportunistic behaviour of suppliers in luring away the corporate customers by offering them superior services or by reducing the leverage of the bank (by having control on the flow of information and finances between the investment bank and the corporate customer) in the Ba-IB-CC triad. Also, not having an accurate credit check of the corporate customer by the corporate bank might result in adverse consequence to the bank presenting wrong information to its stakeholders on returns of their investments. In case of a high default risk and the inability of the bank and the corporate customer to pay the expected interest rates for the bonds, this would harm bank's reputation and could lead to future financial losses. The participants did not mention any particular disruptions in CB-In-IB, CC-In-IB, and CC-In-CB service triads, which seems logical since members of these triads do not interact much in the corporate bonds network. The vulnerability of the whole supply network equals the aggregated vulnerability of its individual triads.

Following a similar procedure, we conducted the same analyses for the remaining three corporate bonds networks and we calculated vulnerability scores for the identified triadic structures in those networks. Table 4.3 illustrates the vulnerability scores obtained for all the four corporate bond networks. Tejarat Bank seems to be having the highest overall vulnerability score among the four banks investigated with triads CB-CC-Ba, CB-CC-IB, and In-CB-Ba showing a significantly higher vulnerability than the other three banks. Looking closer at the adjacency matrices of Tejarat's corporate bonds members, we found that in those particular triads the internal vulnerability of Tajarat's corporate bank (CB node) is the root cause of the sudden increase in the permanents (i.e., vulnerability scores). Thus, Tejarat bank should be advised to overview the processes associated with the bond issuance and underwriting with its own corporate bank. The same type of comparison could be made between other identified triads in the corporate bond networks of the four banks, thus culminating into identifying the most vulnerable node in the network.

Table 4.3 Comparison of the vulnerability scores between the four identified corporate bond networks

Triad type	Mellat	Melli	Tejarat	Saman
IB-Ba-CB	986	810	1170	618
CB-CC-Ba	135	189	567	175
Ba-IB-CC	448	282	162	210
CB-CC-IB	222	282	666	162
CC-Ba-In	30	50	270	42
In-CB-Ba	378	52	462	196
In-IB-Ba	210	430	224	430
CB-In-IB	0	0	0	0
CC-In-IB	0	0	0	0
CC-In-CB	0	0	0	0
Total vulnerability score	2409	2095	3521	1833

Note: *for the sake of space, the complete name of the network is replaced by the name of the banks (e.g., 'Mellat corporate bonds network' is replaced by 'Mellat').*

The outcomes reported in Table 4.3 were shared with and double-checked by a number of key informants from all four banks, along with the representatives of corporate and investment banks, to assure internal and external validity (Barratt et al., 2011; Stuart, McCutcheon, Handfield, McLachlin, & Samson, 2002). In several separate meetings with the aforementioned representatives from each of the four corporate bonds networks, we communicated the main cause(s) of vulnerability in the network. The nature of these causes could either be relational or residing within a specific member of a given supply chain triad. The representatives confirmed that in fact our findings reflected what seemed to be the main problem in the bond issuance and underwriting processes of their corporate bond networks.

Concluding remarks and future research

The present study aimed to address the issue of vulnerability in supply networks and specifically in service supply networks through the lens of service triads. Considering service triads as most elementary form of complex adaptive systems and the building block of service supply networks, the study used the modelling apparatus of graph theory to model a variety of pathways according to which disruptions may emerge and propagate in service networks. In our approach to vulnerability assessment, we adopted the notion of matrix permanent to quantify vulnerabilities which may be induced by various configurations of risk emergence and propagation within supply chain triads.

The suggested analytical approach allows to visualize disruption pathways as graph models and to calculate, based on the notion of matrix permanent, the corresponding vulnerability scores associated with specific configurations of service triads. To demonstrate the relevance of the suggested analytical approach for modelling service triads and calculation of the associated vulnerability levels, a case study grounded in the context of corporate bonds issuance in Iran, was conducted. The adopted analytical approach allowed us to identify the most vulnerable triadic structures in the corporate bonds network and to make a number of cross-case comparisons for a selective number of those service triads. Overall, the approach allowed us to increase visibility of risks emerging and propagating in the context of service supply networks.

The example used in this study showed how the application of graph theory in evaluating vulnerability of service networks through the prism of service triads can be construed as a gateway to more sophisticated supply networks with more nodes and vertices. Several types of supply networks such as block-diagonal, scale-free, centralized, and diagonal (as explored by Kim et al. (2015) could be investigated for their vulnerability levels in various industrial and service contexts. Moreover, for supply networks with significant differences in their triad types (according to the MAN labelling), additional correspondence analyses could be carried out to understand the patterning of triad space in terms of its mutual, asymmetric and null dyads (Faust, 2006), which helps better understanding the types and frequencies of risk relations in supply networks.

Finally, the fact that the suggested graph theoretical modelling approach has been successfully implemented in our study to support the visualization of risk propagation pathways and for vulnerability assessment in the context of corporate bonds issuance in Iran, opens the opportunity to apply this method in the context of other service industries across the globe and replicate our findings in new supply network contexts.

4.4. Chapter summary and conclusion

This chapter investigated risk assessment in service triads. Supported by the emerging theory of the supply chains, complex adaptive systems (Carter et al., 2015) and graph theory, we extracted the various possible triadic structures in which risks could emerge and propagate within the triad. We argued that, so far in the literature, only a handful of these different types of triads have been identified and studied, whereas in our case study we showed that many other types of those triads have a high possibility of existence in supply networks. We also used the assessment tool of matrix permanent to assign values to the vulnerability levels in the identified types of the triads.

Using a case study of several bond-issuing and underwriting supply networks in Iran and a multi-method approach, we tested our proposed model in comparing similar triads among the aforementioned supply networks to identify the most vulnerable interrelations and supply network members.

The application of graph theory in supply network risk assessment is a growing area of research in the field and, considering the analytical capabilities of graphs in simplifying and analysing complex networks, would promise even more avenues for supply chain risk management research in the future.

-CHAPTER FIVE-

-Conclusion and Discussions-

5.1. Overview

The studies undertaken in this thesis aimed at providing an alternative understanding of risks in supply chains and supply networks. The three main pillars of this research were: (i) analysing operational risks in both supply chain tiers and the whole supply chain system and identifying bottlenecks in supply chains, (ii) investigating the role of behavioural anomalies in causing or intensifying operational risks in supply chains, and (iii) identifying new sources of risks emerging and propagating in supply networks through the prism of supply chain triads.

Each of these three research streams is a growing area in the supply chain risk management literature that would require more in-depth research to provide means of better understating vulnerability assessment and resilience in supply chains and supply networks.

To achieve the aims of this research, which consisted of a comprehensive coverage of operational and behavioural risks and their assessment in the number of papers presented, the multi-method approach was deemed most appropriate. In most of the papers presented, initially an analytical model was designed and then tested using the different types of data obtained from archival sources, interviews, surveys or behavioural experiments. This way the compatibility of the analytical models was evaluated and, if necessary, the models were revised to be aligned with the practical needs of supply chain decision makers and managers. Section 5.2 discusses the key findings of the research, in the context of the research questions proposed in Chapter One. Section 5.3 reviews the application of these findings in research and practice, and Section 5.4 presents the limitations and identifies possible future research to eliminate some of these limitations.

5.2. Summary of findings

Inspired by systems theory, as well as the emerging theory of the supply chain proposed by Carter et al. (2015), in Chapter Two it was asked if risk levels in supply chain tiers were different from the whole supply chain system and, if so, which resilience improvement measures should be undertaken to enhance both tier-specific and system-wise resilience in supply chains and to lessen the effects of the identified sources of risk. Using the modelling apparatus of network DEA, it was found that indeed sometimes there could be significant differences between overall supply chain resilience to risks and the resilience of its individual members. For instance, if the supply chain shows high levels of overall resilience, but a few of its tiers suffer from medium to high levels of vulnerability to risks, the whole supply chain operations could be jeopardized as the case of vulnerability in that specific tier intensifies. In fact, the act of identifying vulnerable members of supply chains toward risk is a precautionary action to eliminate risks from causing disruptions in the supply chain processes.

The similar model was tested again in the context of a service supply network in the banking industry, using archival data. The analysis of the results showed how the performance of several public and private commercial banks and their service supply chains can be evaluated simultaneously. Statistical inference testing of the results shed light on differences in performance of public and private banks interest-bearing operations. The results also showed how outsourcing to external entities could influence the overall efficiency of a supply chain, either positively or negatively.

Chapter Three focused more on behavioural risks in terms of the intersection between behavioural and operational risks, and also the attitudes of supply chain decision makers toward risks and the impact of these attitudes on their ordering decisions. For the first study in this chapter, again the same analytical model (i.e., network DEA) was used to evaluate performance of different supply chain tiers in the banking industry of Iran, but this time the research delved deeper into the relations and human interactions between different supply chain tiers and how this affected the collaboration and collective performance in those supply chains. It was found most of the inefficiencies identified were that in fact caused by behavioural factors that damaged the quality of relations between members in the corporate bond issuing and underwriting network.

The second study in Chapter Three focused specifically on risk attitudes of decision makers and whether the models for risk aversion/risk seeking, loss aversion, or prospect theory could explain ordering behaviours in supply chains. To this end a behavioural experiment was conducted using the beer distribution game on MBA and undergraduate students. The results showed that the aforementioned models cannot fully predict the ordering decisions in supply chains. In fact, subjects were more inclined to under-order when they were expecting losses and over-order when they were making profits. Among the interesting findings of this study that subjects with higher scores in statistical numeracy and risk literacy tests performed significantly better in the beer game, compared with the others.

In Chapter Four, another nascent view of supply chain risks – the study of risks in triads – was investigated. Borrowing from the principles of graph theory, the various forms of triads in which risks could emerge and propagate were investigated and their minimum and maximum vulnerability scores were calculated. Looking closely at the literature, the study found that there are still numerous types of triads not investigated in the literature that could expose supply networks to high amounts of vulnerability. Focusing again on the banking industry and service triads, it was shown how these triads could be identified and evaluated among similar supply networks in the same industry.

5.3. Implications for research and practice

Although the implications for research and practice are already mentioned in the papers included in previous chapters, this section summarizes the main implications of those studies.

Operational risks and resilience in supply chains (first paper in Chapter Two)

A better insight into resilience to supply chain risks could be gained by assessing resilience both at the level of individual tiers and as the whole supply chain system. The dual perspective on supply chain resilience assessment was therefore suggested to minimize the adverse effects of the realised risks upon individual tiers and the overall supply chain.

The results of the empirical analysis showed that the resilience level associated with the overall supply chain did not necessarily indicate the resilience of its individual tiers. Similarly, high efficiency scores of a number of tiers forming a supply chain had only a limited effect on the overall efficiency score of the resulting supply chain. This supported previous studies investigating the characteristics of emergence and complexity as fundamental properties accounting for non-linearity in the behaviour of the supply chains (Carter et al., 2015; Choi & Krause, 2006). These characteristics have also been reported as detrimental for the visibility of individual supply chain members (Carter et al., 2015; World Economic Forum, 2013), including the ability to visualize risks of the supply chain members (Neiger et al., 2009).

The research findings confirmed the necessity of adopting both the system-wide and tier-specific approach by analysts and decision makers when assessing supply chain resilience. From the top-down perspective, such an approach should consider the structure of the supply chain and potential threats, both internal and external, associated with its core value drivers and deliverables. The bottom-up approach would consider the threats associated with inflows, outflows, resources and key deliverables associated with supply chain partners and thereby directly contributing to the overall level of the supply chain resilience. Hence, a realistic measure of the overall supply chain resilience can be achieved only through the coordinated effort of all parties in terms of the assessment of risks associated to the overall supply chain or one of its components. Such a composite assessment of supply chain resilience at both the systems and tier levels facilitates identifying any substantial differences in efficiency scores across distinct tiers of supply chains. Integrated as part of the risk response and mitigation process, such information ensures timely identification and mitigation of major sources of risk in the supply chains.

Outsourcing performance assessment (second paper in Chapter Two)

This paper contributed to the outsourcing and supply chain risk management literature by evaluating a significant set of processes in internal and external entities. The processes can be evaluated using multiple factors (i.e., multiple operational risk measures) that could affect quality and performance in supply chains that outsource their operations to external entities.

The hybrid network DEA model introduced in the paper incorporated exogenous and endogenous inputs and outputs used to prepare the final product or service offered by an outsourcer. By combining the hybrid network DEA model with a general SBM approach, limitations of traditional network DEA models in terms of pre-specification of weights for processes and relatively low discrimination power of these models were eliminated. SBM also enabled the network DEA models to account for weakly efficient DMUs, hence increasing the accuracy of the results.

The analytical model is applicable to a larger context of manufacturing and services supply chains with flexibility for performance measurement metrics selected. The model is mostly suitable when there is information asymmetry between different tiers in supply chains and when the outsourcer's knowledge and understanding of the processes related to external upstream or downstream supply chain members are limited.

Behavioural and operational risks in supply chains (first paper in Chapter Three)

This study found that managers should pay equal attention to operational and behavioural factors when addressing inefficiencies within supply networks. It was recommended that, in the context of the corporate bonds, network managers take the following steps to help overcome inefficiencies caused by behavioural issues throughout their supply network:

(i) Having identified and acknowledged the employees' goals regarding the quality of services they offer to the issuer, managers should implement a control and feedback mechanism to constantly monitor individuals' motivation levels, thereby keeping employees of investment banks or corporate banks motivated enough to provide quality services to issuers.

(ii) Managers should then apply control mechanisms and supervision over issuers (especially the investment bank) to preclude them adopting opportunistic behaviour. The latter should also be addressed by strengthening trust levels between bank and issuer.

(iii) Managers should also implement debiasing strategies to reduce the impact of identified behavioural biases (e.g., anchoring, overconfidence, suck costs fallacy) on the quality of decisions made by providing warnings and awareness about the decision biases, decomposing complex decision tasks into smaller components, and applying multiple perspectives to view decision tasks (Kaufmann et al., 2009; Tokar et al., 2012). Other debiasing measures to be taken in supply chains can reduce the effects of dynamism in the decision-making context (Haines et al., 2010; Kaufmann et al., 2009). Overall, the extent of dynamism in the environment moderates between rational and comprehensive decision making and decision quality (Hough & White, 2003). Reducing dynamism in the corporate bond network requires identifying changes in business and updating marketing strategies for the bonds, and applying tools and mechanisms that could detect and address changes in both external and internal operational and behavioural factors affecting efficiency in this network. Furthermore, unambiguous information could help reduce complexities in the decision-making environment, leading to fewer biases in the decision-making process (Kaufmann et al., 2009). This could be achieved in the corporate bond network by developing databases that could capture and analyse all information relevant to the operational and behavioural factors identified in this study. In fact, gathering information more frequently and efficiently, especially in dynamic environments such as supply networks, is believed to be critical to engage decision makers in "procedural rationality" as an important decision-making approach (Haines et al., 2010; Riedl et al., 2013).

Risk attitudes and ordering behaviour of supply chain decision makers (second paper in Chapter Three)

This study identified several research and practical implications:

- Risk aversion and risk seeking models can only partially predict ordering behaviour, and especially when subjects incur losses.
- Loss aversion cannot predict the ordering behaviour of participants in multi-echelon supply chains.
- Prospect theory is inconclusive about the ordering behaviours and therefore cannot be used to make predictions about ordering decisions in supply chains.
- For the games with the addition of the revenue parameter, none of the models was applicable to the results.
- Subjects with higher scores in the BNT test showed a better performance in the games. There were no significant differences observed in the performance of participants according to their sex, age or relevant work experience.
- Overall, when the outcomes were all losses (loss game), subjects tended to under-order, whereas when the outcomes could be both gains and losses (gain game), subjects were more inclined to over-order.

Service triads and the assessment of vulnerability in them (book chapter and paper in Chapter Four)

The application of the graph theory allowed calculating the Risk Index as an implicit quantitative measure of risk, in line with the structural and relational properties of the underlying dyadic structures informed by the RaST typology. The suggested approach provided a quick and intuitive tool for risk assessment and ranking of RaSTs in line with their type and group within the RaST typology. In other words, suggested graph analytical approach allowed us to visualize disruption pathways as graph models and to calculate, based on the notion of matrix permanent, the corresponding vulnerability scores associated with specific configurations of service triads. This approach also helped us to identify the most vulnerable triadic structures in the corporate bonds network and to make a number of cross-case comparisons for a selective number of those service triads.

5.4. Limitations and future research

Each paper presented in the thesis had its particular caveats and implications for the future research based on the context of that study. This section summarizes those limitations and implications for future research.

Risk and resilience assessment paper (first paper in Chapter Two)

The proposed DEA model for risk and resilience assessment in supply chains did not explicitly capture the effects of reverse causality and feedbacks between the actors (or major processes) within the system, which should be clearly regarded as a limitation of the approach. The model also failed to capture product of non-linear dynamic behaviour, such as time delays. The task of addressing these properties was beyond the scope of the paper, and so this is a possible future research direction. It would be best to address this task by using the reach toolset of system dynamics modelling, or a hybrid simulation approach which would– depending on the goal of the follow up study – draw upon the integrated use of system dynamics and agent-based modelling, system dynamics and discrete event simulation, or even on the integration of these three simulation modelling approaches. Such aggregated use of multiple simulation modelling approaches is supported by such simulation engines as AnyLogic (among others) and would certainly represent a very interesting research avenue for building and testing supply chain resilience assessment models.

In addition, the precision of resilience assessment in supply chains could be improved by incorporating supply chain orientation and the firm's resource reconfiguration capabilities, in line with another holistic supply chain resilience assessment framework recently proposed by Ambulkar et al. (2015). Finally, the suggested fuzzy network DEA model for supply chain resilience assessment was validated in a country-specific setting comprising nine major industry sectors of Iran. To increase external validity of the model, further studies might test the model in the context of other countries and regions to see whether the reported discrepancy between the resulting system-wide and tier-specific resilience assessment scores are observed in other settings.

Future studies might further explore the applied aspects of supply chain performance and resilience assessment. They could adopt different methodological approaches to improve the assessment of supply chain resilience at various levels – moving from a system-wide perspective of the supply chain toward an organization-specific perspective of individual supply chain tiers. For instance, structural models could be developed that link supply chain risk variables to supply chain resilience variable(s). These models could be empirically tested in different industrial and services contexts to determine the severity of impact for each risk group on supply chain resilience. Furthermore, the results of this study demonstrated that risk assessment throughout supply chain tiers may not be analogous across industries, highlighting the need to further explore the boundary conditions of the proposed model.

Outsourcing performance assessment (second paper in Chapter Two)

The inputs and outputs of the DEA model used in the paper involved merely quantifiable and financial criteria that are more accessible and easy to measure. However, for qualitative assessment criteria (e.g., Srinivasan & Kurey, 2014) to be incorporated in the model, more sophisticated approaches such as fuzzy network DEA (Kao, 2014c) could be leveraged to address the uncertainties associated with the aforementioned criteria. Application of the α-cut approach (Kao & Liu, 2011) was suggested to overcome this issue. Despite additional discrimination power of the DEA model when combined with the SBM measure, the number of DMUs needed to be significantly larger than basic DEA models to ensure that the results have sufficient discrimination power. Moreover, the proposed model in this study was developed to assess quality of performance for outsourcing in service supply chains. Using this model in more operational and manufacturing contexts requires primarily revisiting the inputs, outputs and intermediate products in the manufacturing supply chain, such as production and procurement facilities, speed to market, or safety (for a full list of relevant metrics see, Gunasekaran et al., 2015).

Overall, this paper provided some additional foundation for modelling and evaluation of outsourcing services, especially from a quality perspective. Evaluation and benchmarking with respect to cost, flexibility, time and other measures can be easy extensions, provided data are available. Given the importance of outsourced activities and internal process implications, data that help integrate and link the broader supply chain will need to be captured. Tools such as the one provided here can help organizations identify performance measures and relevant analytical models within the outsourcing context. Ample opportunities exist for future research to build upon the foundation set by this study, not only in this context, but in a more general context of performance evaluation of outsourced activities.

Behavioural and operational risks in supply chains (first paper in Chapter Three)

While this paper envisioned mainly decision-making-related scenarios that could be disrupted by decision makers' bounded rationality, the results from the case analysis showed additional behavioural issues present in the bilateral relations throughout the corporate bond network. From this aspect, a limitation of this study framework was that it adopted a general approach toward all the behavioural issues identified in the DEA modelling of the network. Analysing specific behavioural factors in supply networks would provide more in-depth knowledge of the root causes of errors in judgment and decision making, although such analyses would be limited in number because of the over-complexity of the behavioural models.

A second limitation is that semi-structured interviews and critical incident techniques were utilized to gain insight into the behavioural misconducts within the banking industry, despite some authors arguing that laboratory experiments are preferable (Knemeyer & Naylor, 2011) because they control for irrelevant biases that might cause errors in the final results of the analyses. Thus it is recommended that researchers consider incorporating behavioural factors into their performance and efficiency assessment models of supply networks in order to improve the application of these models to real-world problems. Moreover, the outcomes of this study suggest that decision makers should be more aware of intangible variables, including those behavioural factors in their interrelations with their counterparts in supply networks in general and in the corporate bond service networks in particular.

Risk attitudes and ordering behaviour of supply chain decision makers (second paper in Chapter Three)

First, the paper did not use the decision weights of the prospects in its proposed analytical models. The main reason for this was the abundance of different prospects at each period of the game which culminate in the estimations of their probabilities being inaccurate. Moreover, each game and supply chain tier would have had different prospects at each stage of the game, and this would make the inclusion of decision weights even more complicated. Future research could be conducted in a more controlled beer game setting with only a handful of prospects available to the subjects so that estimations of decision weights will be possible.

Second, the modelling section did not include the ordering decision rule by Sterman (1989b) or the alternative simplified model proposed by Croson and Donohue (2006) that account for subjects' bounded rationality in terms of underweighting quantities of inventory, demand or supply line. There are several reasons for this decision. First, it could be mathematically shown that the parameters introduced in the aforementioned studies for ordering decisions do not affect the predictions of the already developed analytical models in the paper. Second, mixing those models with either one of the risk models used in this study would add at least one more parameter (α, λ or both) for estimation and, as a rule of thumb, that would require at least 10 weeks in addition to a beer game already 36 weeks long for the total amount of observations to be sufficient for parameter estimation and model fit comparison. The latter could be investigated as a separate research article in the future.

Risk assessment in service triads (book chapter and paper in Chapter Four)

Several types of supply networks, such as block-diagonal, scale-free, centralized and diagonal (as explored by Kim et al., 2015), could be investigated for their vulnerability levels in various industrial and service contexts. Moreover, for supply networks with significant differences in their triad types (according to the MAN labelling), additional correspondence analyses could be carried out to understand the patterning of triad space in terms of its mutual, asymmetric and null dyads (Faust, 2006), which helps better understand the types and frequencies of risk relations in supply networks.

5.5. Concluding remarks

This thesis and the articles included in it explored new directions in the field of supply chain risk management. To achieve this, three main lines of research were investigated in depth, and resulted into several published and working papers presented in three separate chapters (Chapters Two–Four) in this study. In general, the main differentiating factors between these three chapters were the types of risks (operational, behavioural or both) or the supply chain structure (network and triads vs. traditional vertical supply chains) under investigation.

Considering the applicability of the topic of this research in the real-world practices of global supply chains, the findings obtained by each of the research papers presented in this thesis can shed light on how supply chain decision makers could assess, prioritize and address risks and disruptions considering the dynamics of their supply chains.

The author also hopes that each of the aforementioned research topics would draw the attention of researchers specifically in the field of supply chain risk management and behavioural supply chain management to conduct more holistic yet in-depth studies into the realm of the intersection of human behaviour, operations and the risks emerging and propagating from them throughout supply networks.

Finally, it is worth noting that given the lack of theories and theory building specific to operations and supply chain management, the application of mixed-methods approaches or, on a higher level, research approaches such as design science (Hevner, March, Park, & Ram, 2004; Holmström et al., 2009) could be a leap forward into both connecting research and practice and also developing and testing new theories.

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APPENDICES

Appendix 1. Survey instrument

Instruction: Please evaluate the exposure to the following risks of your industry's supply chain using the following scale::

Extremely low, Low, Fair, High, and Extremely high.

Then, using the same scale, please evaluate the resilience level of your industry's supply chain in face of the risks indicated below.

Upstream risks

Dependence of manufacturer on a single source of supply.

Opportunistic behaviour of supplier.

Poor logistics performance of supplier.

Quality problems of supplier.

Financial instability of supplier.

Inadequate responsiveness of suppliers to changes in demand, technologies, and rules/regulations.

Organizational risks

Infrastructure problems (e.g., IT system failure, machine breakdown, etc.).

Quality and safety issues related to labour and manufacturing processes.

Abrupt changes in product's specifications.

Human resources-related issues (e.g., disputes, strikes, civil unrests, etc.).

Operational inflexibilities (e.g., financial, inventory, and capacity inflexibilities).

Downstream risks

Volatile customer demand.

Poor logistics performance of distribution channels (e.g., transportation disruption, excessive delivery cost/time, faulty assignments of products to customers).

Network risks

Lack of trust between supply chain members.

Low level of visibility and information asymmetry among supply chain members.

Order oscillation and amplification among tiers in supply chains.

External risks

Man-made risks (e.g., political instability, changes in regulations, civil unrests, strikes, war, etc.)

Natural hazards (natural disasters, diseases or epidemics, etc.)

Resilience (Human capital resources)

Education and training of employees to execute supply chain contingency plans

Employee's understanding of cost/benefit trade-offs when managing risk in a supply chain

Ability to perform post-disruption analysis

Resilience (Organizational and inter-organizational capital resources)

Defined communication protocols
Cross-functional supply chain risk management teams
Predefined and/or self-executing contingency plans
Partnering with customs programs (such as C-TPAT) and/or developing port diversification plans
Developing supplier relationship management programs
Resilience (Physical capital resources)
Use of safety stock
Increased visibility in the supply chain
Exception reporting systems and predictive tools for early awareness of impending disruptions
Risk monitoring systems for each node (i.e., firm) in the supply chain
Ability to quickly redesign the supply chain

Appendix 2. Profile of the interviews

No.	Organization	Respondent's functional position	Date (2013-2014)
1	Mellat Bank	Head of Corporate Banking Division	18 December
2	Eghtesad Novin Bank	Head of Research and Planning Centre	20 December
3	Amin Investment Bank	Head of the Investment Bank	25 December
4	Omid Investment Bank	Head of the Investment Bank	31 December
5	Melli Bank	Member of Board of Directors	8 January
6	Omid Investment Bank	Head of Financial Risk Mgt. Division	16 January
7	Novin Investment Bank	Head of the Investment Bank	22 January
8	Melli Bank	Head of Retail Banking Division	24 January
9	Saman Bank	Member of Board of Directors	30 January
10	Novin Investment Bank	Head of Financial Risk and Controlling	5 February
11	Sepehr Investment Bank	Director, Research and Development	9 February
12	Saman Bank	Member of Board of Directors	12 February
13	Amin Investment Bank	Head the Investment Bank	14 February
14	Sepehr Investment Bank	Director, Risk Analysis and Mgt. Division	20 February
15	Corporate Client #1*	Director, CFO Division	28 February
16	Corporate Client #2*	Head of Strategic Management	3 March
17	Corporate Client #3*	Director, CFO Division	6 March
18	Corporate Client #4*	Director, CFO Division	10 March
19	Investor representatives#1*	-	18 March
20	Investor representatives#2*	-	23 March
21	Investor representatives#3*	-	25 March
22	Investor representatives#4*	-	28 March

* *To maintain confidentiality of the information entrusted by the nominated banks and investment banks to the authors, names of corporate clients and investor representatives are not revealed in this study.*

Appendix 3. Interview protocol: Corporate client's perspective

<table>
<tr><th colspan="2">Interview info</th><th>Respondent's information:</th></tr>
<tr><td colspan="2">Interview number:
Date:
Time:
Location:
Co-interviewer:</td><td>Full name:
Age:
Position:
Working experience in finance (years):
Years in current position:</td></tr>
<tr><th colspan="2">Guidelines and Questions</th><th>Observations</th></tr>
<tr><td colspan="2">Appreciating the respondent for his/her participation and appointment.
Explaining the research purpose and scientific terms required to respond to the questions.
Explaining the risks/benefits of participation.
Explaining their withdrawal rights.
Asking if they have any concerns/questions.
Getting their permission to use the voice recorder.
Turning on the voice recorder.</td><td></td></tr>
<tr><th>A</th><th>General info</th><th>[Ice breaking and building rapport with the respondent]</th></tr>
<tr><td>Q01</td><td>Please tell us about your main responsibilities (History, Products/ Services).</td><td></td></tr>
<tr><td>Q02</td><td>Please tell us about the tasks associated with your position relevant to negotiating with underwriters and bank representatives (responsibilities, reporting, how many people you manage).</td><td></td></tr>
<tr><td>Q03</td><td>Describe situation(s), if any, which you considered to be adversely affecting your relations with the corporate bank and/or bank that provides your company a variety of financial services.</td><td></td></tr>
<tr><td>Q04</td><td>Could you share your opinion about the core behavioural drivers that caused such situation(s)?</td><td></td></tr>
<tr><th>B</th><th>Stage I</th><th>[Main questions/answers]</th></tr>
<tr><td>Q05</td><td>How much has the adverse situation(s) affected your manner of cooperation with the underwriter and/or the bank in the bond underwriting processes? Please explain and prioritize.</td><td></td></tr>
<tr><td>Q06</td><td>How likely are you to choose the same bank and/or investment/corporate bank as your underwriter and issuer again? Please explain and prioritize.</td><td></td></tr>
</table>

C	**Stage II**	
Q07	How much do you think the quality of relations between the bank and the underwriter has caused the adverse situations that you experienced? Please explain and prioritize.	
D	**Stage III**	
Q08	How much do you think the quality of relations between the bank and the investors has caused the adverse situations that you experienced? Please explain and prioritize.	

Appendix 4: Online beer game settings and instructions

Figure A1 Beer game supply chain layout

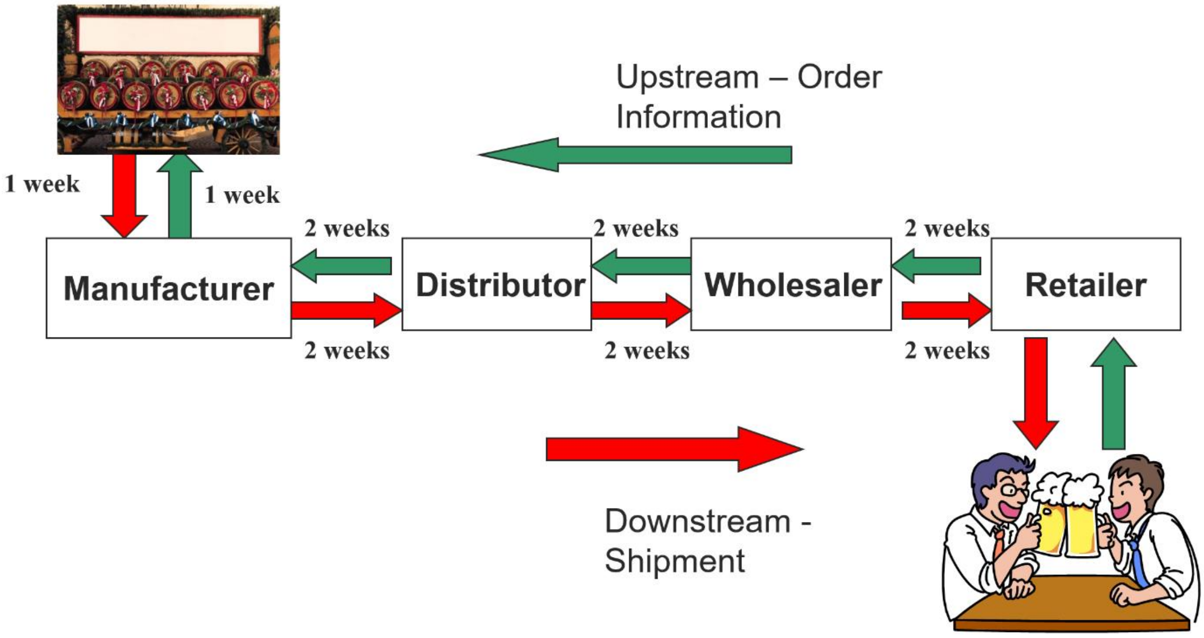
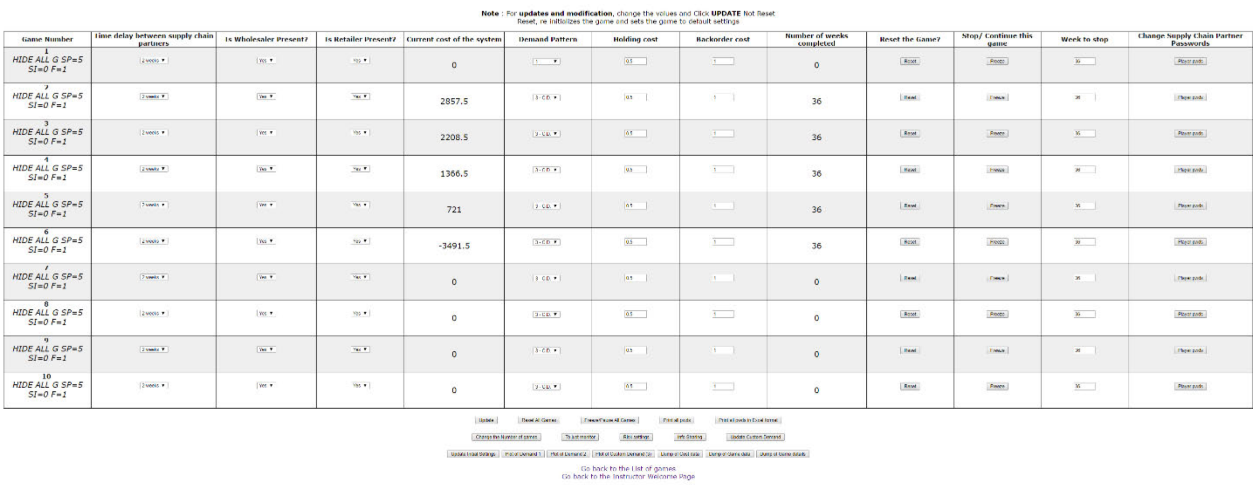


Figure A2 Instructor page



Note : For **updates and modification**, change the values and Click **UPDATE** Not Reset
Reset, re initializes the game and sets the game to default settings

Game Number	Time delay between supply chain partners	Is Wholesaler Present?	Is Retailer Present?	Current cost of the system	Demand Pattern	Holding cost	Backorder cost	Number of weeks completed	Reset the Game?	Stop/ Continue this game	Week to stop	Change Supply Chain Partner Passwords
1 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	0	1	0.5	1	0	Reset	Freeze	36	Player pwds
2 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	2857.5	3 - C.D.	0.5	1	36	Reset	Freeze	36	Player pwds
3 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	2208.5	3 - C.D.	0.5	1	36	Reset	Freeze	36	Player pwds
4 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	1366.5	3 - C.D.	0.5	1	36	Reset	Freeze	36	Player pwds
5 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	721	3 - C.D.	0.5	1	36	Reset	Freeze	36	Player pwds
6 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	-3491.5	3 - C.D.	0.5	1	36	Reset	Freeze	36	Player pwds
7 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	0	3 - C.D.	0.5	1	0	Reset	Freeze	36	Player pwds
8 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	0	3 - C.D.	0.5	1	0	Reset	Freeze	36	Player pwds
9 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	0	3 - C.D.	0.5	1	0	Reset	Freeze	36	Player pwds
10 HIDE ALL G SP=5 SI=0 F=1	2 weeks	Yes	Yes	0	3 - C.D.	0.5	1	0	Reset	Freeze	36	Player pwds

Update | Reset All Games | Print all pwds | Print all pwds in Excel format
Change the Number of games | To just monitor | Risk settings | Info Sharing | Update Custom Demand
Update Initial Settings | Plot of Demand 1 | Plot of Demand 2 | Plot of Custom Demand (3) | Dump of Cost data | Dump of Game data | Dump of Game details
Go back to the List of games
Go back to the Instructor Welcome Page

On this page the game instructor can determine the settings of the game including the number of echelons, weeks, cost parameters, lead times and demand pattern.

Figure A3 Game status

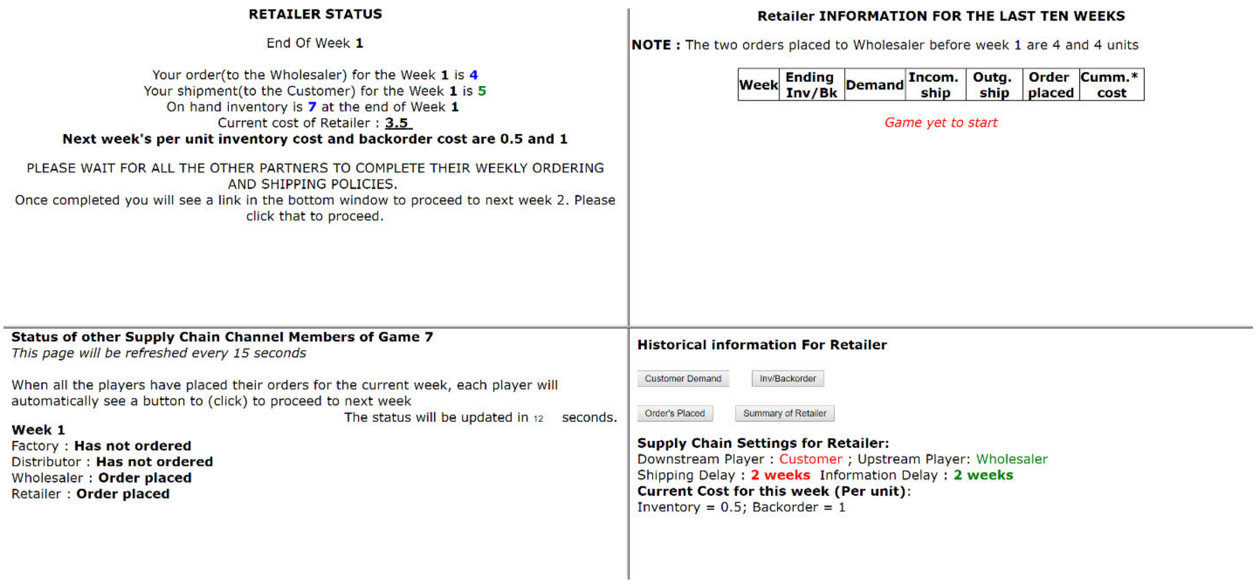
Refresh Status | Ranking to Display in Class without current weeks | Ranking to Display in Class | Go Back

Game number	Game settings Delay, Holding Cost, Backorder Cost	Total Cost Week completed	Factory Cost Week completed	Distributor Cost Week completed	Wholesaler Cost Week completed	Retailer Cost Week completed	Graphical plots	Stop/ Continue the game
1	2 weeks , 0.5, 1	Cost : **0** W.C. : 0	Yet to start.	Yet to start.	Yet to start.	Yet to start.	Plots	Freeze
2	2 weeks , 0.5, 1	Cost : **2857.5** W.C. : 36	Cost : **882.5** W.C. : 36	Cost : **744.5** W.C. : 36	Cost : **580** W.C. : 36	Cost : **650.5** W.C. : 36	Plots	Freeze
3	2 weeks , 0.5, 1	Cost : **2208.5** W.C. : 36	Cost : **760** W.C. : 36	Cost : **361** W.C. : 36	Cost : **577** W.C. : 36	Cost : **510.5** W.C. : 36	Plots	Freeze
4	2 weeks , 0.5, 1	Cost : **1366.5** W.C. : 36	Cost : **-16** W.C. : 36	Cost : **325.5** W.C. : 36	Cost : **540** W.C. : 36	Cost : **517** W.C. : 36	Plots	Freeze
5	2 weeks , 0.5, 1	Cost : **721** W.C. : 36	Cost : **-276** W.C. : 36	Cost : **9.5** W.C. : 36	Cost : **382** W.C. : 36	Cost : **605.5** W.C. : 36	Plots	Freeze
6	2 weeks , 0.5, 1	Cost : **-3491.5** W.C. : 36	Cost : **-4254** W.C. : 36	Cost : **-273** W.C. : 36	Cost : **595.5** W.C. : 36	Cost : **440** W.C. : 36	Plots	Freeze
7	2 weeks , 0.5, 1	Cost : **0** W.C. : 0	Yet to start.	Yet to start.	Yet to start.	Yet to start.	Plots	Freeze
8	2 weeks , 0.5, 1	Cost : **0** W.C. : 0	Yet to start.	Yet to start.	Yet to start.	Yet to start.	Plots	Freeze
9	2 weeks , 0.5, 1	Cost : **0** W.C. : 0	Yet to start.	Yet to start.	Yet to start.	Yet to start.	Plots	Freeze
10	2 weeks , 0.5, 1	Cost : **0** W.C. : 0	Yet to start.	Yet to start.	Yet to start.	Yet to start.	Plots	Freeze

Freeze/Pause All Games

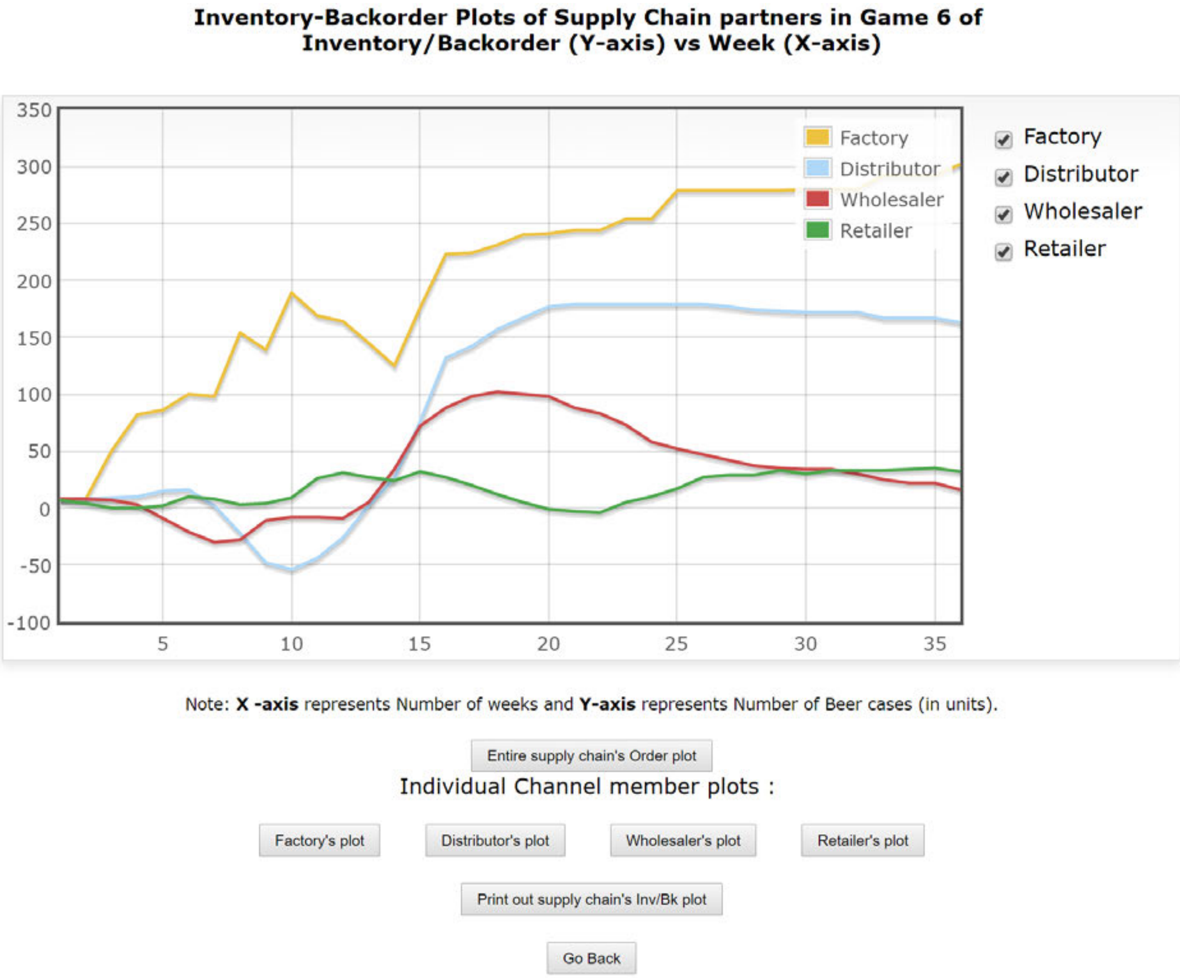
This page shows the real-time status of the games as they proceed. The plots on this page were used to explain the bullwhip effect to the participants after the game.

Figure A4 Game screen



There are four quadrants to the game screen. Participants can place their orders and be informed of their inventory status in upper left quadrant. The summary of the status for several consecutive games is provided in the table in the upper right quadrant. The inventory, cost and demand plots are accessible in lower right quadrant. The lower left quadrant informs the participant about the status of other supply chain members.

Figure A5 Result screen



The result screen is provided to the participants after the game is complete. The plots on the result screen are used to show the participants the bullwhip effect.

Appendix 5: Pre-game BNT survey

Please do not discuss the answers and complete it on your own.

Please answer the questions below. Do not use a calculator but feel free to use a scratch paper or notepad. It should take you less than five minutes.

Question 1: Imagine we are throwing a five-sided die 50 times.On average, out of these 50 throws how many times would this five-sided die show an odd number (1, 3 or 5)

- 5 out of 50 throws
- 25 out of 50 throws
- 30 out of 50 throws
- None of the above

Question 2: Out of 1,000 people in a small town 500 are members of a choir. Out of these 500 members in the choir 100 are men. Out of the 500 inhabitants that are not in the choir 300 are men. What is the probability that a randomly drawn man is a member of the choir? Please indicate the probability in percent

- 10%
- 25%
- 40%
- None of the above

Question 3: Imagine we are throwing a loaded die (6 sides). The probability that the die shows a 6 is twice as high as the probability of each of the other numbers. On average, out of these 70 throws, about how many times would the die show the number 6?

- 20 out of 70 throws
- 23 out of 70 throws
- 35 out of 70 throws
- None of the above

Question 4: In a forest 20% of mushrooms are red, 50% brown and 30% white. A red mushroom is poisonous with a probability of 20%. A mushroom that is not red is poisonous with a probability of 5%. What is the probability that a poisonous mushroom in the forest is red?

- 4%
- 20%
- 50%
- None of the above

Appendix 6. Permanent calculation formula of the RaST adjacency matrix

$$A = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

$$\boldsymbol{Per}\ (\boldsymbol{A}) = r_{11}r_{22}r_{33} + r_{11}r_{23}r_{32} + r_{22}r_{13}r_{31} + r_{33}r_{12}r_{21} + r_{12}r_{23}r_{31} + r_{13}r_{21}r_{32}$$

Appendix 7. Profile of the interviews

No.	Organization	Interviewee's functional position	Date (2012-2013)
1	Mellat Bank	Head of Corporate Banking Division	18 December
2	Mellat Bank	Head of Research and Planning Center	20 December
3	Amin Investment Bank	Head of the Investment Bank	25 December
4	Omid Investment Bank	Head of the Investment Bank	31 December
5	Melli Bank	Member of Board of Directors	8 January
6	Omid Investment Bank	Head of Financial Risk Management Division	16 January
7	Novin Investment Bank	Head of the Investment Bank	22 January
8	Tejarat Bank	Head of Retail Banking Division	24 January
9	Saman Bank	Member of Board of Directors	30 January
10	Novin Investment Bank	Head of Financial Risk Planning and Controlling Division	5 February
11	Sepehr Investment Bank	Director, Research and Development Department	9 February
12	Saman Bank	Member of Board of Directors	12 February
13	Amin Investment Bank	Head the Investment Bank	14 February
14	Sepehr Investment Bank	Director, Risk Analysis and Management Division	20 February
15	Corporate Customer #1*	Director, CFO Division	28 February
16	Corporate Customer #2*	Head of Strategic Management	3 March
17	Corporate Customer #3*	Director, CFO Division	6 March
18	Corporate Customer #4*	Director, CFO Division	12 March
19	Investors' Representatives #1*	Director, CFO Division	18 March
20	Investors' Representatives #2*	Director, CFO Division	20 March
21	Investors' Representatives #3*	Director, CFO Division	27 March
22	Investors' Representatives #4*	Director, CFO Division	3 April

* To maintain confidentiality of the information entrusted by the nominated banks and investment banks to the authors, names of corporate customers are not revealed in this study.

Appendix 8. Interview protocol: Corporate customer's perspective

Interview info

Interview number:
Date:
Time:
Location:
Co-interviewer: ☐

Interviewee's information

Full name:
Age:
Position:
Working experience in finance (years):
Years in current position:

Guidelines	**Observations**
• *Appreciating the interviewee for his/her participation and appointment.*	____________
• *Explaining the research purpose and scientific terms required to respond to the questions.*	____________ ____________
• *Explaining the risks/benefits of participation.*	____________
• *Explaining their withdrawal rights.*	____________
• *Asking if they have any concerns/questions.*	____________
• *Getting their permission to use the voice recorder.*	____________
• *Turning on the voice recorder.*	__________

Questions

Q01	Please tell us about your working experience in this position and your main responsibilities.
Q02	Please explain the main risk drivers in your internal processes that if realized could disrupt your active role in the corporate bonds network. Please prioritize (Likert 1-10 scale).
Q03	Describe situation(s), if any, which you considered to be adversely affecting your relations with the corporate bank and/or bank while receiving services for issuing and underwriting bonds .
Q04	How much has the adverse situation(s) affected your manner of cooperation with the investment bank and/or the bank in the bond underwriting processes? Please explain and prioritize(Likert 1-10 scale).
Q05	Describe situation(s), if any, which you considered to be adversely affecting your relations with the investment bank and/or bank while receiving services for issuing and

	underwriting bonds.
Q06	How much has the adverse situation(s) affected your manner of cooperation with the investment bank and/or the bank in the bond underwriting processes? Please explain and prioritize(Likert 1-10 scale).

Appendix 9. Ethics Approval Letter [Ref. 5201500565]

RE: Ethics Application - Final Approval
Send to: Chief investigator/Supervisor
CC: Co-Investigator or Co-Investigators

Subject Line: - Final Approval-

Dear Dr Keblis,

RE: 'A Study of Risk and Loss Aversion in Multi-Echelon Supply Chains '
(Ref: 5201500565)

The above application was reviewed by the MGSM Ethics Sub-Committee. The MGSM Ethics Sub-Committee wishes to thank you for your well-written application. Approval of this application has been granted, effective "29/07/ 2015". This approval constitutes ethical approval only.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:

Chief Investigator: Dr Matthew Keblis
Other Personnel: Mehrdokht Pournader

NB. STUDENTS: IT IS YOUR RESPONSIBILITY TO KEEP A COPY OF THIS APPROVAL EMAIL TO SUBMIT WITH YOUR THESIS.

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).

2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 29/07/ 2016
Progress Report 2 Due: 29/07/ 2017
Progress Report 3 Due: 29/07/ 2018
Progress Report 4 Due: 29/07/ 2019
Final Report Due: 29/07/ 2020

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

5. Please notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:

http://www.mq.edu.au/policy/
http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have final approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of Final Approval to an external organisation as evidence that you have Final Approval, please do not hesitate to contact the FHS Ethics at the address below.

Please retain a copy of this email as this is your official notification of final ethics approval.

Yours sincerely,

Chair
MGSM Ethics Sub-Committee
